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Trends in an Environmental Nitrogen Management Index across Europe reveal progress since 1980s but also required considerable improvements

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Highlights

- A composite indicator (ENMI) was developed to assess sustainable nitrogen (N) management
- ENMI integrates environmental thresholds (N surplus) with productivity targets (N output)
- Sub-national ENMI assessment reveals strong regional disparities in N management across the EU
- Between 1960 and 1980, the average ENMI stayed constant since higher yields came at the cost of higher N surpluses
- After 1980 the average ENMI decreased, mainly due to lower N surpluses at com-

parable crop yields

- Despite improved management practices, there are still large gaps between current and attainable crop yields and critical N surpluses

Science for Society

Nitrogen (N) is essential for food production, but excess N from agriculture pollutes water, air, and ecosystems across Europe. Despite decades of efforts to reduce these impacts, many regions still exceed safe environmental limits, while agricultural productivity must be maintained to feed a growing population. Balancing these two needs remains a major challenge, and clear guidance is needed to identify where N use is sustainable and where action is most urgent. Our study introduces the Environmental Nitrogen Management Index (ENMI), a simple tool that shows whether regions use N within safe limits while producing enough food. Applying ENMI over the past 60 years reveals progress since the 1980s, but also large regional differences. While some areas have reduced N pollution, others continue to pose risks to the environment. ENMI helps decision-makers target interventions, design effective N policies, and plan pathways toward sustainable food systems that protect both the environment and human well-being.

Summary

Nitrogen (N) inefficiency threatens both environmental sustainability and food production in European agriculture, with many regions facing high levels of N pollution. Addressing the dual challenge of sustaining productivity while reducing environmental harm requires an integrated, spatially explicit indicator. We present the Environmental Nitrogen Management Index (ENMI) — a threshold-based, composite indicator that captures agricultural productivity (N yield relative to regional target yield) and environmental pressure (N surplus relative to regional safe N surplus). ENMI ranges from 0 (worst) to 1 (sustainable: no adverse impacts at target yield). Applied across EU sub-national regions from the 1960s to 2010s, ENMI rose from 0.07 to 0.21, with disparities from 0.76 in Switzerland to below 0.1 in parts of Eastern Europe. A 2030 scenario analysis shows that ambitious N input cuts improve environmental outcomes but reduce yields. ENMI offers a transparent basis to assess sustainability progress and guide policy interventions on N management.

Introduction

Sustainable nitrogen (N) management is a key aspect in meeting the dual challenge of modern agriculture: feeding a growing population while reducing environmental impacts. Although N inputs are essential for high crop yields and food security, their excessive use leads to a range of environmental impacts - including air and water pollution with related biodiversity loss and human health impacts, and greenhouse gas emissions[1–4].

The central sustainability question is how to reconcile the competing goals of productive agriculture and environmental protection.

Feeding a growing population within safe regional N boundaries requires an integrated management approach that accounts for both agricultural productivity needs and environmental constraints[5]. In Europe, the EU's Farm to Fork (F2F) Strategy aims to halve nutrient losses by 2030 while maintaining soil fertility[6]. In this context, agricultural N surplus - defined as the difference between total N inputs and outputs - has become a central metric. It represents the total N losses from agricultural systems and is thus directly linked to environmental pressures. To define a safe N surplus level, critical N surplus thresholds have been derived across the globe that correspond to the maximum allowable losses, which can support policymaking[7,8]. Reducing agricultural N surplus by increasing the N use efficiency (NUE) — the ratio of N output to N input — is a crucial step toward minimizing overall N losses[9–11]. However, focusing on N surplus alone is not enough; sustainable N management must also ensure adequate N output i.e., the N removed with harvested crops and animal grazing, to meet the needs for food production[12].

To address this dual imperative, the Sustainable Nitrogen Management Index (SNMI) was developed, combining crop yield and NUE[13]. In the first SNMI assessment, NUE was normalized against a fixed reference value of 1 and reference crop yield was set at 90 kg N ha^{-1} (considering a globally averaged yield target for meeting food demand in 2050), with both values applied uniformly across countries and calculated at the national scale. While

valuable for global assessments, these universal thresholds and national-level aggregation limit its ability to capture region-specific targets for N yield and NUE, and to prioritize N management strategies that reconcile both goals at sub-national level. To tackle this limitation, the SNMI was adjusted with more realistic fixed NUE targets of 0.8 and 0.9 and the universal reference yield was replaced with region-specific attainable yields[13]. Nevertheless, the proposed adjustment still assumes a constant reference NUE for the whole area, thereby ignoring the actual variation in required NUE in view of environmental impacts related to acceptable N losses[12,14]. For example, in a regional subsystem with high denitrification, N losses might be acceptable at a moderate NUE, while a very high NUE is needed in a system with low denitrification. Thus, the challenge to meet acceptable N losses to the environment is thus poorly met by using NUE.

To overcome these limitations, we introduce a spatially explicit Environmental Nitrogen Management Index (ENMI): a threshold-based, distance-to-target metric that quantifies how far a region lies from sustainable N management. ENMI integrates (i) the N surplus ratio — which is the actual N surplus relative to a critical N surplus threshold (i.e. the safe environmental limit for water quality and biodiversity[8]), and (ii) the N yield ratio — which is the actual N yield relative to a spatially varying attainable yield or target yield[8], denoted as reference yield (see Methods for details). ENMI is calculated as the Euclidean distance from the sustainability target point (1,1), representing a system that keeps N surplus at or below the environmental threshold while achieving N yields at or above the target (reference) yield, thereby meeting both environmental and productivity

goals. ENMI values range from 0 (high environmental impacts at low crop yields) to 1 (no adverse environmental impacts at target crop yield), offering an intuitive and biophysically grounded way to measure N management performance while accounting for biophysical and agronomic constraints that vary over space. Unlike relative efficiency indicators, ENMI is anchored in absolute thresholds and designed to enable spatially explicit tracking of N productivity and environmental impacts at sub-national levels, thereby supporting sustainability assessments[10,14].

In this study, we apply the ENMI framework to evaluate N management across the EU-27 from the 1960s to the 2010s using harmonized gridded N surplus datasets[15]. We examine temporal and spatial trends at NUTS levels (Nomenclature of Territorial Units for Statistics) to assess whether there have been overall improvements towards sustainability, and to determine whether sustainability gains have come from yield improvements, reductions in N surplus (below critical levels), or both (see Methods). We also investigate regional disparities, identify leading and lagging areas, and analyze historical trade-offs between the two ENMI dimensions. Finally, we explore the implications of three forward-looking policy scenarios for 2030[9] (see Methods) to assess the development and/or alignment of ENMI within EU nutrient reduction targets (e.g., F2F strategy[6]). By linking environmental thresholds to food production goals, ENMI provides a new lens for evaluating and guiding sustainable N governance. In this study it is applied to EU-27, but it can be adapted to other regions worldwide.

Results

Trends in ENMI at the EU-27 level

The averaged ENMI value for all EU-27 member states increased from 0.07 in the 1960s to 0.21 in the 2010s, indicating a gradual shift towards more sustainable N management by improving agricultural productivity and/or reducing environmental pressures (Figure 1a). However, this improvement has been driven primarily by a steady rise in the N yield ratio (food production axis) – from 0.39 to 0.57 – while the N surplus ratio (safe environment axis) changed only marginally, from 0.30 to 0.34. This imbalance suggests that most gains have come from enhanced food production, whereas reductions in N losses have lagged behind. As shown in Figure 1b, the agricultural productivity component improved more consistently and strongly than the N surplus component across time and countries. The limited progress in N surplus reduction has become a bottleneck in achieving greater sustainability. In the 2010s, country-level ENMI values vary widely within the EU, indicating uneven performance (Figure 1a). Some countries – including Switzerland (CH), Ireland (IE), and the United Kingdom (UK) – are positioned closest to the sustainability target in ENMI space (values of 0.76, 0.75, and 0.68, respectively), reflecting more balanced N use. In contrast, several member states remain far from the optimal point (1,1), due to persistent environmental excess or under-performance in productivity. Together, these trends highlight that while the EU as a whole is progressing, large disparities remain among regions, highlighting the importance of spatially targeted

strategies to accelerate sustainable N management.

Spatial patterns in ENMI performance

While EU-wide trends point to gradual improvement in N management since the 1960s, aggregate values can obscure substantial heterogeneity both within and across countries. To better identify where progress has occurred and where challenges persist at sub-national scale, we examined decadal ENMI trajectories at NUTS-1 level (Figure 2). For clarity, values shown for each decade represent the average across all years within that decade (e.g. 1960 corresponds to 1960–1969). To test the robustness of the decadal aggregation, we also calculated these trajectories using shorter averaging windows. Supplementary Figure S1 presents 3-year centered means (e.g., 1960 $=$ 1960–1962), and Supplementary Figure S2 presents 5-year centered means (e.g., 1960 $=$ 1960–1964). Both approaches yield patterns consistent with the decadal results shown in the main text.

Over the past five decades, N yield ratios, reflecting agricultural productivity relative to a reference level, have steadily improved across Europe, contributing to rising ENMI values at the continental scale (Figure 2). In contrast, progress in reducing N surplus has been far less uniform. From the 1990s onward, regions in Central and Eastern Europe began showing signs of improvement, yet by the 2010s, many areas still reported N surplus ratios well below the sustainability threshold (i.e., $\leq$0.4), indicating continued N excess. Conversely, regions such as northern Sweden have consistently maintained

N surplus ratios at 1, reflecting long-term alignment between N inputs and environmental thresholds. This is supported by national statistics, such as Swedish farming systems, which report declining agricultural N surplus since the 1990s, high NUE ($\approx$69%), and reduced ammonia emissions[16]. On the productivity side, most regions in Western and Central Europe have steadily improved their N yield ratios and by the 2010s approached target levels. However, regions in parts of Eastern and Southeastern Europe continue to lag behind, highlighting persistent productivity gaps. These spatially contrasting pattern are further reflected in the combined ENMI indicator i.e., while performance was poor across much of Europe in the 1960s and 1970s — with nearly 80% of regions recording ENMI values below 0.4 — gradual improvements became evident from the mid of 1980s onward. By the 2010s, this share had fallen to about 55%, highlighting notable progress but also the persistence of wide regional inequalities (Figure 2). For example, Germany's (DE) national ENMI score in the 2010s was relatively low (0.19; Figure 1a), driven largely by poor environmental performance (N surplus ratio $= 0.21$) despite strong productivity (N yield ratio $= 0.87$). Yet, western and southern regions (e.g., Baden-Württemberg, Saarland) perform much better (ENMI$\sim$0.56), while eastern regions (e.g., Saxony, Thuringia) continue to underperform (ENMI$\sim$0.15) (Figure 2). Spain (ES) shows a similar pattern: the national ENMI of 0.40, shaped by a low N surplus ratio (0.40) combined with high productivity (0.90), conceals sharp internal variation. Northwestern regions (e.g., Galicia and Cantabria) perform close to the sustainability target (ENMI$\sim$0.96), whereas central regions (e.g., Madrid) scored much worse (ENMI$\sim$0.16).

Furthermore, two regions may exhibit equally poor ENMI scores, but for different reasons, underlining the importance of decomposing ENMI into its environmental and agricultural productivity components. For instance, in the eastern Netherlands (e.g., Overijssel, Gelderland), ENMI in 2010 showed 0.05 — one of the worst in Europe — despite a high N yield ratio (0.92). The is due to extremely low N surplus ratio (0.05; with an actual N surplus of more than 150 kg N ha^{-1}), which has severe environmental consequences. By contrast, southwestern Poland had a similarly low ENMI (0.09), but its poor score stemmed from low productivity (N yield ratio = 0.53) and only moderately low N surplus ratio (0.22). These contrasting cases underscore the importance of interpreting ENMI components separately, in the Netherlands, addressing environmental overload is the priority, while in Poland, increasing N output through more efficient input use is critical.

Temporal dynamics in regional ENMI trajectories

To evaluate how N management has evolved at the regional level over time, we analyzed decadal changes in ENMI scores across NUTS-1 regions, as shown in Figure 3a. Here, each decade label refers to the transition into that decade. For example, 1970s denotes the change between the 1960s and 1970s ($ENMI_{1970s}$ – $ENMI_{1960s}$). Each value is computed as the difference between the average ENMI score in one decade and the preceding decade. Positive changes greater than 0.05 (shaded green) indicate improved performance, negative changes below –0.05 (purple) reflect worsening, and intermediate values (beige) represent relative stability.

In the early decades (transitions from the 1960s to the 1970s and from the 1970s to the 1980s), a majority of regions remained relatively stable. For instance, from the 1960s to 1970s, 55% of NUTS-1 units (65 out of 118) exhibited minimal change, while 37% worsened, particularly in regions of the United Kingdom, France, and Poland. Only 8% improved including Ireland, Northwestern Spain and some regions in Turkey. The following decade (from the 1970s to the 1980s) showed similar pattern: 76% of regions stayed stable, while only 14 improved. These included regions that had already shown progress in the earlier decade (e.g. Ireland, northwestern Spain, Turkey), along with new regions depicting improvement in Belgium and parts of Sweden (Figure 3a).

A notable shift began from the mid of 1980s to the 1990s. During this period, 42% (49 regions) improved with many of them located in Northern and Central Europe. These general patterns are consistent with previous analyses showing declining N surpluses in Europe since the mid-1980s[9,12]. This improvement coincides with the introduction of environmental regulations such as the Nitrates Directive[17,18] and broader socio-economic changes across Europe that curbed excessive fertilizer use and promoted better agricultural practices[9,11,12,19]. Only a few regions deteriorated, suggesting an overall continental shift toward improved N management. This positive momentum continued from the 1990s to the 2000s, particularly in Central Europe and the Baltic region. However, 63 sub-national (NUTS) regions still does not show appreciable improvement and remained stagnant, which indicate that there are still obstacles to N management improvements in those regions. From the 2000s to the 2010s, improvements in ENMI peaked: 49% (58

regions) saw increasing ENMI values across Europe. Notable progress occurred across France, the United Kingdom, Southern Germany, and parts of Eastern Europe. Nonetheless, pockets of ENMI stagnation and even deterioration persisted in Western Europe and Southern Europe, reflecting uneven progress.

To better disentangle the changes in ENMI, Figure 3b presents scatter plots showing the decomposition of ENMI trends into changes in N yield ratio (x-axis) and N surplus ratio (y-axis). Each point represents a NUTS-1 region, with color indicating the direction of ENMI change. The upper-right quadrant contains regions with balanced improvements — i.e., those that increased N yield while simultaneously reducing environmental pressures via lowering N surplus. These ”win–win” cases were rare in the earlier decades (only about 3% of regions between 1960s and 1970s), but became increasingly common over time, reaching $\sim$26% from 1980s and 1990s and $\sim$35% in the transition during 2000s and 2010s. These percentages refer only to regions in this quadrant that showed an improvement in ENMI (green points in Figure 3b). However, many regions still show unbalanced progress: points in the lower-right quadrant improved agricultural productivity but experienced no gains (or even setbacks) in environmental performance, while points in the upper-left quadrant reduced N surplus but failed to improve productivity. These contrasting trajectories highlight both the encouraging increase in integrated improvements and the persistent difficulty of achieving them universally, highlight the need for region-specific strategies that address both productivity and environmental constraints (further discussed below).

ENMI in 2030 under future scenarios

Achieving sustainable N management requires concurrent improvements in productivity (N output) and reductions in environmental losses (N surplus). To assess how far European regions remain from this dual objective – and how different policy pathways might help close the gap – we evaluated three illustrative future scenarios for 2030 across NUTS-1 regions (Figure 4). First, the Green Deal Fertilizer (GD-F) assumes a 20% reduction in synthetic fertilizer use without adverse impacts on crop yield. Second, the FAO Fertilizer scenario (FAO-F) assumes a deeper fertilizer cuts (43%) combined with improved Technological and Management Practices (TMPs). The third FAO Fertilizer and Manure (FAO-FM) scenario additionally restricts manure use (4%) on top of the FAO-F scenario. The three scenarios increasing in their ambition and related intervention strategies are evaluated against the 2015–2019 baseline, consistent with the EU Green Deal guidelines, which use this period as the reference frame[6,15] (see Methods for detail).

At the EU-27 level, all scenarios lead to modest improvements in ENMI compared to the baseline. The GD-F scenario achieved a ENMI score of 0.30 – driven by improved environmental performance (N surplus ratio $=$ 0.44) while maintaining productivity (N yield ratio $=$ 0.57). The FAO-F and FAO-FM scenarios yielded slightly better ENMI scores (0.34 and 0.35, respectively). However, these gains are achieved primarily through reduced N surplus (ratios of 0.55 and 0.57, respectively), with decreasing productivity (N yield ratios $=$ 0.52 and 0.51 , respectively). These results highlight the more balanced nature of the

GD-F scenario, which offers environmental benefits with only limited productivity losses.

The spatial analysis of sustainability gaps – defined as the distance to the optimal value of 1 for both N surplus and N yield ratios – further clarifies the above scenario-specific differences (Figure 4b). Across the EU, more regions met the target for N surplus than for N yield. Under FAO-FM, 25% of NUTS regions fully closed the N surplus gap, compared to 23% under FAO-F and 17% under GD-F. Conversely, the highest share of regions reaching the yield target (N yield ratio $= 1$) occurred under GD-F (3%), while both FAO-F and FAOF-M scenarios reached just 1%. Despite these gains, only two NUTS-1 regions (northern Sweden and northwestern Spain) achieve the ideal sustainability point (ENMI $= 1$) under the GD-F scenario. This underscores the inherent difficulty of simultaneously improving both productivity and environmental performance – especially under stringent nutrient reduction strategies. Overall, while all scenarios lead to some improvement, approaches like FAO-F and FAOF-M deliver relatively modest, one-dimensional gains i.e., advancing environmental metrics but compromising productivity; and therefore fall short of closing the overall sustainability gap.

Discussion

Insights obtained from trends in ENMI across Europe

Over the past six decades, achieving sustainable nitrogen (N) management has become a central challenge for European agriculture. Intensification since the 1960s has in-

creased crop yields through greater N inputs, but also driven environmental degradation, including air and water pollution and biodiversity loss[10,11]. In response, European policy frameworks — such as the EU Green Deal and the F2F Strategy — have called for integrated solutions that reduce nutrient losses without compromising food production[6]. This study contributes to that agenda by introducing the Environmental Nitrogen Management (ENMI) Index: a threshold-based, distance-to-target metric that jointly assesses environmental pressure and agricultural productivity. ENMI values increased modestly for the EU-27 — from 0.07 in the 1960s to 0.21 in the 2010s — signaling progress, yet large regional disparities remain. Between 1960s and 1980s, the average ENMI stayed constant since higher yields came at the cost of higher N surpluses. After 1980 the average ENMI decreased, mainly due to lower N surpluses at comparable crop yields. Sub-national ENMI assessment reveals strong regional disparities in N management across the EU. Many NUTS-1 regions continue to deviate substantially from the dual sustainability target of reducing N pollution while maintaining productivity. Despite improved management practices, there are still large gaps between current and attainable crop yields and critical N surpluses.

Potential role of ENMI in policy making

Our scenario analysis highlights the potential of different nutrient and food production related policy pathways. All three 2030 scenarios, which are presented as examples to demonstrate ENMI's application, show improved ENMI scores relative to the

2015–2019 baseline, although the balance between productivity and environmental gains varies. It should be noted, use of the ENMI in policymaking is limited to nutrient loads and agricultural productivity. Other policy priorities, such as expanding organic farming or carbon sequestration, involve trade-offs[20] are not represented in the ENMI. For example, increasing the prevalence of organic farming systems often involves using more organic N inputs, which has a positive effect on carbon sequestration, but this leads to lower N productivity[21] and often also enhances the soil N surplus. To reflect such policy dimensions, the ENMI indicator needs to be expanded with other indicators, as different objectives emphasise different aspects of sustainability.

In our scenarios, productivity gains partly rely on improved Technological and Management Practices (TMPs), represented through changes in the yield response to N input (see Methods). We assumed a continuation of the historical trend of TMPs improvement up to 2030, which captures gradual progress in measures such as precision fertilization, nitrification inhibitors, and improved crop varieties[22,23]. This reflects a moderate, evidence-based projection of sustainable intensification. However, past progress has been uneven and generally slower than required, and achieving the scenario outcomes would demand much faster and broader adoption of TMPs than observed historically. Notably, our scenario analysis focuses on the near future (2030), it assumes current land use and climate remain unchanged and under these conditions, some regions may still be constrained by strict N surplus thresholds. Accelerating TMPs deployment will face major barriers — including institutional and economic constraints, geopolitical risks, and

societal resistance to dietary change[24–26]. Achieving ENMI targets will therefore require coordinated strategies that align agronomic innovation with governance, incentives, and behavior change[9,27]. Crucially, ENMI's dual-axis design allows policymakers to assess whether nutrient loss reductions are achieved without compromising production — a central tension in the F2F Strategy[6]. This makes ENMI a policy-relevant indicator for guiding, monitoring, and evaluating sustainability transitions along these dual challenges.

Role of ENMI in assessing hotspots for sustainability improvement

A defining feature of ENMI is its use of absolute biophysical thresholds. The critical N surplus, representing the maximum allowable N surplus before environmental harm occurs in view of water quality and biodiversity goals[8], was adapted regionally in our study to account for ecosystem-specific sensitivity to N pollution. Its inclusion ensures ENMI aligns not just with efficiency goals, but with ecological safety limits. Similarly, the reference N yield reflects regional productivity potential under attainable agronomic conditions for cropland and pasture[8]. Together, these thresholds anchor ENMI in both environmental and production realities. Specifically, by operating at the sub-national (NUTS-1) level, ENMI uncovers regional disparities often masked by national averages. For example, western Germany performs substantially better than the eastern regions, and the Madrid region lags behind other parts of Spain. This granularity enables more targeted interventions and resource allocation. In terms of temporal resolution, ENMI can be applied annually or over multi-year averages; in this study we use the latter to smooth interan-

nual variability, but the metric is flexible enough to track both short-term policy effects and long-term structural changes on field, farm, regional and continental level.

ENMI also helps diagnose which sustainability dimension needs attention. For instance, regions with high yields but high surplus (e.g., parts of the Netherlands) require pollution control, while others with low surplus but poor yields (e.g., parts of Eastern Europe) need productivity support. ENMI thus functions not only as a performance metric but also as a indicator for tailored, region-specific action. Disaggregating the index into its underlying component ratios is essential for further diagnosis.

Limitations and Recommendations for further improvements

Despite the potential of ENMI in policy making, some limitations should be acknowledged. First, the critical N (surplus) thresholds used here are taken from Schulte-Uebbing et al.(2022)[8], where they were derived for conditions around 2010. These thresholds, combine uniformly applied criteria for N deposition, surface water quality (using N concentration in runoff as a proxy), and groundwater quality. For surface waters, for example, a single threshold of 2.5 mg N L^{-1} is used, even though reported safe limits vary widely across water types, from 0.5 to 4.0 mg N L^{-1}[28]. Moreover, although the thresholds themselves are temporally constant (but spatially varying), actual runoff and leaching can vary over time with different meteorological (e.g., rainfall, temperature) and land-use conditions. Relying on static thresholds and multi-year averages may therefore highlight long-term patterns but miss inter-annual variability of hydrologic conditions (e.g., runoff). In ad-

dition, while Europe-specific critical N surplus is available[29], we relied on a global dataset[8] because it consistently provides both N surplus thresholds and reference yield estimates for the European domain. This ensured internal consistency across dimensions of ENMI but comes at the cost of some loss in regional specificity. Future refinements could improve these estimates by integrating Europe-specific thresholds as they become more comprehensive.

Second, the reference N yield is defined as a maximum attainable productivity benchmark, but food security within Europe can often be ensured at lower yield levels depending on self-sufficiency, trade, and dietary demand[30]. In addition, crop biodiversification over space and time will have impacts on both the N surplus as the N yield, potentially altering the future path of ENMI and giving opportunities to move to the desired state faster then projected here. Using maximum yields of the current cropping system as the benchmark may therefore overstate the N input needs (mainly fertilizer and manure).

Third, ENMI relies on aggregated N surplus, which masks differences between its sources — fertilizer, manure, biological fixation, or atmospheric deposition — that may require distinct policy responses[31] since the environmental impact varies among these N sources[32]. It overlooks the positive contribution of organic N buildup to soil health, being associated to the desired carbon increase in soils given the 4-promille (4p1000) initiative[33].

Finally, ENMI is limited to agricultural N and does not include non-agricultural sources

such as sewage discharges, which can contribute substantially to water pollution in some regions[34]. This means ENMI should be interpreted as an agricultural sustainability metric, not as a measure of total N pressure on ecosystems. In addition, ENMI focuses on biophysical sustainability and does not directly capture equity, economic viability, or social acceptability.

By identifying progress, persistent gaps, and scenario outcomes, ENMI functions both as a diagnostic lens and as a means to explore solution spaces to develop policy recommendations that balance food security with environmental sustainability. Future extensions should refine the underlying thresholds to better capture regional specificity and changing boundary conditions - for example, using water-body–specific standards or incorporating adjustments for hydrological variability and climate change. Additional improvements could include alternative N yield benchmarks, source-specific surplus accounting, and integration with broader food system indicators such as dietary quality, food affordability, or greenhouse gas emissions[35] to strengthen ENMI's diagnostic and policy relevance. ENMI could also be complemented by other targeted indicators linked to safe boundaries such as freshwater use and biodiversity loss[36], and extended to cover other nutrients (e.g., phosphorus) and farming systems (e.g., livestock). By situating ENMI within such a complementary indicator framework, the proposed index can effectively contribute to assessing agriculture's role in staying within safe and just operating spaces[36]. By combining transparency, scientific rigor, and policy relevance, ENMI offers a powerful indicator for assessing the progress of agricultural systems with long-term environmental

and food security goals.

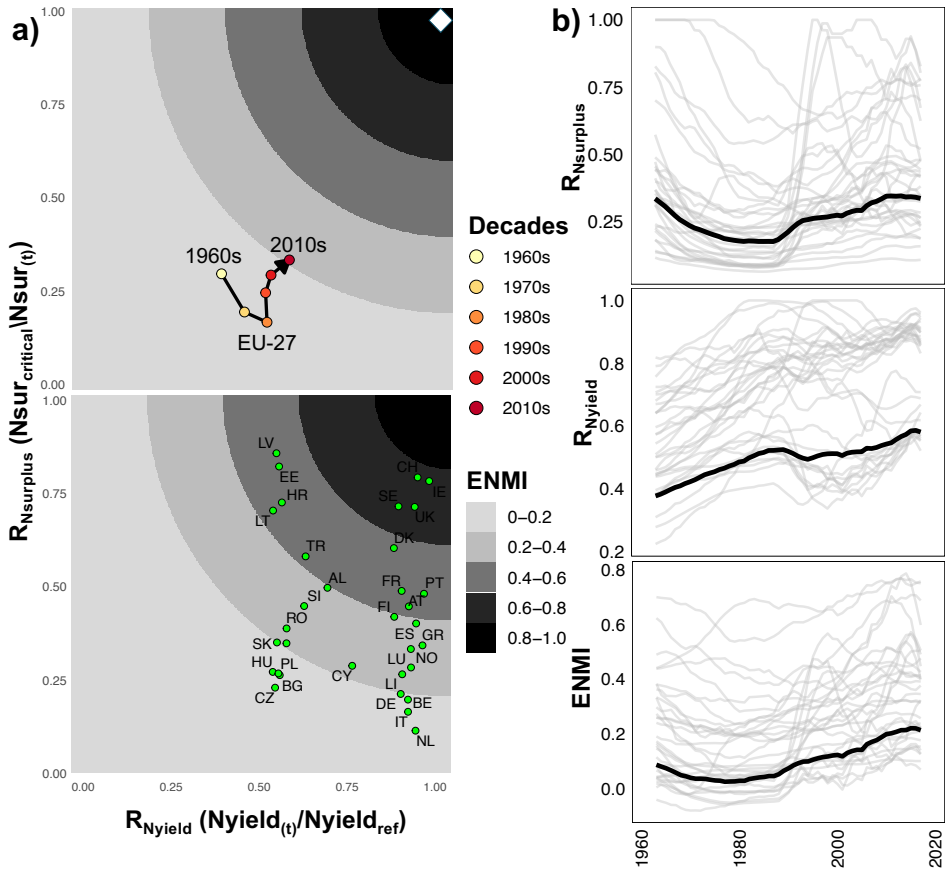


Figure 1: **Evolution and spatial variation in nitrogen management performance across the EU. (a)** Decadal trajectory of EU-27 performance in ENMI (Environmental Nitrogen Management Index) space from the 1960s to 2010s. Each decade represents the mean of all years within that period (e.g. 1960s = 1960–1969). The x-axis shows the N surplus ratio (critical/actual N surplus), where values below 1 indicate excess N pollution and 1 reflects environmental sustainability. The y-axis shows the N yield ratio (actual/reference N output), where values below 1 indicate underperformance in food production. ENMI represents the distance from the sustainability target (white diamond, top-right corner, where both goals are met). The lower panel shows the 2010s performance for individual EU countries in the same ENMI space; movement toward the top-right indicates progress. **(b)** Time series of N surplus ratio (top), N yield ratio (middle), and ENMI (bottom) for EU countries from the 1960s to 2010s (grey lines), with the thick black line showing the EU-27 average.

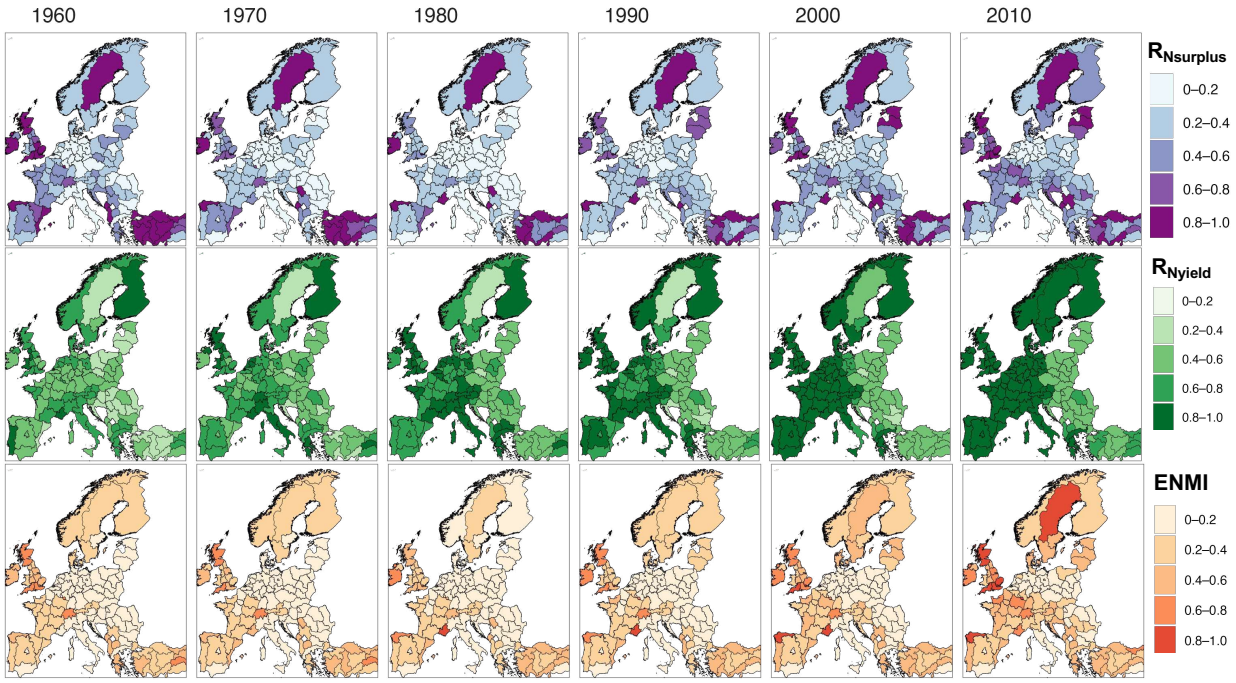


Figure 2: **Spatiotemporal patterns in N management across European regions from the 1960s to 2010s.** Maps show estimates of N surplus ratio (top row), N yield ratio (middle row), and ENMI (bottom row) at NUTS-1 level across six decades. Each decade represents the mean of all years within that ten-year period (e.g. 1960 = 1960–1969). The N surplus ratio (critical / actual N surplus) shows whether regions are within environmental limits. A value of 1 means the threshold is met; values below 1 reflect excess N pollution. The N yield ratio (actual / reference yield) shows progress toward food production targets. Values below 1 indicate underperformance in productivity. ENMI integrates both components into a single index, where higher values indicate better overall N management. Substantial regional variation is visible throughout the decades, with uneven progress in balancing productivity and environmental impact across Europe.

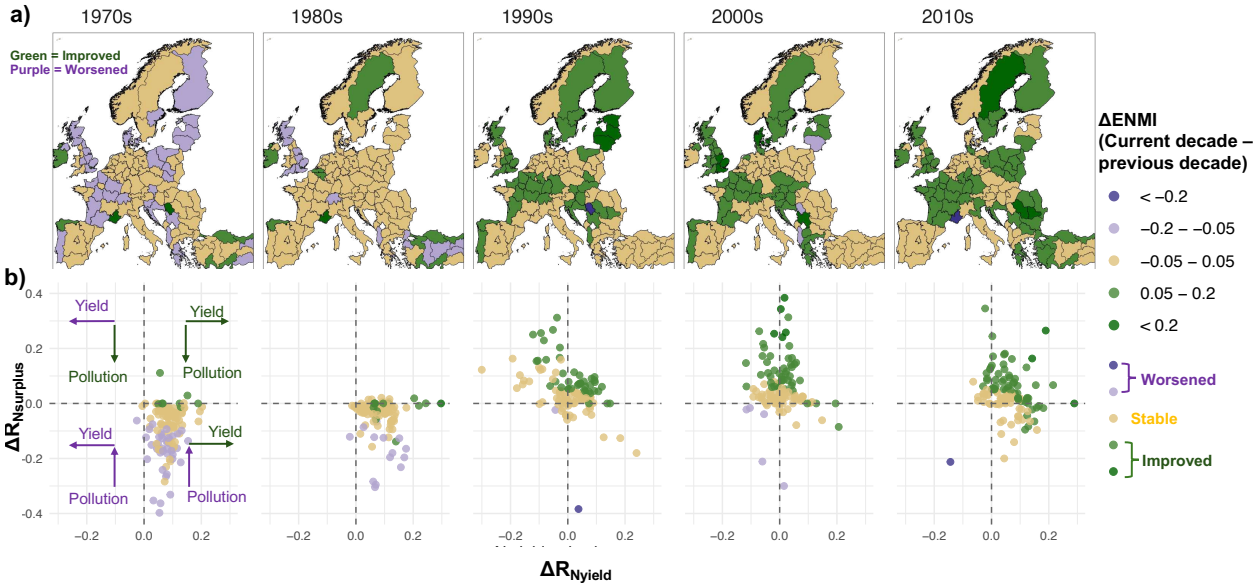


Figure 3: **Decadal changes in ENMI across European regions. (a)** Each panel shows the change in ENMI at NUTS-1 level between consecutive decades (e.g., 1970s $=$ $\text{ENMI}_{1970s} - \text{ENMI}_{1960s}$). Each decade represents the mean of all years within that ten-year period (e.g. 1970s $=$ 1970–1979). Positive values (shaded in green) indicate improved N management (i.e., ENMI has increased and regions are moving closer to the optimal point). Negative values (shaded in purple) indicate worsened performance (i.e., ENMI has decreased, moving further away from the optimal point). Beige areas represent minimal change. (b) Scatter plots show the change in N surplus ratio (y-axis) and N yield ratio (x-axis) for each region at NUTS-1 level in the same decade-to-decade intervals. The color of each point matches the ENMI change from panel (a): green for improved ENMI, purple for worsened ENMI, and beige for little or no change. Arrows indicate how to interpret the different quadrants — ideal (top-right), imbalanced outcomes (bottom-right and top-left), and joint decline (bottom-left).

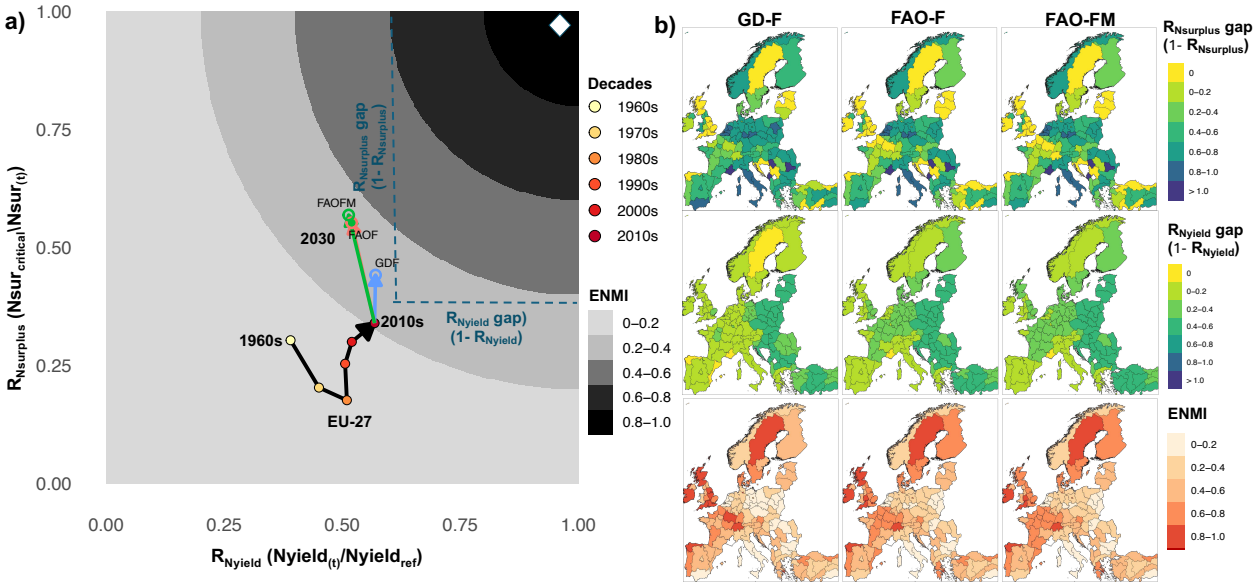


Figure 4: **Projected N management performance of the EU in 2030 under future scenarios.** **(a)** ENMI trajectory of the EU-27 from the 1960s to the 2010s is extended to show projected outcomes under three scenarios for 2030: FAO-F, FAO-FM, and GD-F. The ENMI target (1,1) is shown as an white diamond. The dotted lines indicate remaining gaps to the sustainability target (1) in both N surplus and N yield dimensions. **(b)** Regional estimates of the gap to sustainability for each scenario at NUTS-1 level. The top row shows the gap in N surplus ratio (1 – surplus ratio), and the middle row shows the gap in N yield ratio (1 – yield ratio); in both, lower values indicate better performance (i.e., smaller distance to the target of 1). The bottom row presents projected ENMI values, where higher ENMI indicates more balanced and sustainable N management.

Methods

Environmental Nitrogen Management Index (ENMI)

To evaluate the sustainability of nitrogen (N) management in agriculture, we developed the Environmental Nitrogen Management Index (ENMI), a composite indicator that captures both productivity and environmental pressure in a unified framework. ENMI quantifies the deviation of a system's N performance from a defined sustainability target/optimal point, based on two core dimensions: N surplus and N output (yield).

As with the SNMI, defined by Zhang et al. (2022)[13], the index is calculated as the Euclidean distance from the optimal point (1,1) in a normalized coordinate space (Figure 1a), where:

- The x-axis represents the **N surplus ratio** ($R_{N_{surplus}}$), defined as the ratio of a region's critical N surplus threshold to its actual N surplus.
- The y-axis represents the **N yield ratio** ($R_{N_{yield}}$), defined as the ratio of a region's current N output to a reference N output or yield.

ENMI builds on the distance-to-target concept introduced in the Sustainable Nitrogen Management Index (SNMI)[13], while extending it to explicitly link agricultural performance with N-specific sustainability thresholds.

The ENMI is thus computed as:

$$\text{ENMI}(j,t) = 1 - (\sqrt{(1 - R_{N_{surplus}}(j,t))^2 + (1 - R_{N_{yield}}(j,t))^2}) \quad (1)$$

where j denotes the spatial unit, being the NUTS region, and t the time. This formulation reflects how far a system lies from the ideal/optimal N management point.

This two-dimensional representation allows ENMI to reflect the joint progress (or trade-offs) between food production and N surplus reduction. The closer a system is to the point (1,1), the more balanced and sustainable its N management. Larger deviation from this point indicate underperformance in one or both dimensions. A ENMI value of one indicates perfect alignment with sustainability goals, meaning that N surplus is within the safe threshold and food production meets the reference yield. Lower ENMI values reflect increasing deviation from this balanced target, either due to excess pollution, insufficient production, or both.

N Surplus Ratio

The N surplus ratio ($R_{N_{surplus}}$) is used to assess environmental pressure from agriculture relative to a defined safe boundary. It is calculated as the ratio of a region-specific critical N surplus to actual N surplus at a given regional unit and time:

$$R_{N_{\text{surplus}}}(j,t) = \begin{cases} \frac{N_{\text{surplus}_{\text{critical}}}(j)}{N_{\text{surplus}}(j,t)}, & \text{if } \frac{N_{\text{surplus}_{\text{critical}}}(j)}{N_{\text{surplus}}(j,t)} \leq 1 \\ 1, & \text{if } \frac{N_{\text{surplus}_{\text{critical}}}(j)}{N_{\text{surplus}}(j,t)} > 1 \end{cases} \quad (2)$$

where j refers to the country or NUTS-region, and t is the time. A ratio of 1 indicates alignment with the sustainability threshold. Values below 1 signal exceedance of the environmental limit. Any value above 1 is set to 1, as this occurs when the N surplus is below the threshold and therefore meets the environmental target.

The critical N surplus values used in this study are drawn from Schulte-Uebbing et al. (2022)[8] are based on thresholds derived from three key environmental criteria: 1) N deposition to natural ecosystems (to protect terrestrial biodiversity); 2) N concentration in runoff to surface water (to prevent aquatic eutrophication); 3) N concentration in groundwater (to safeguard drinking water quality). The N surplus is then derived as the minimum of the three estimates.

We used the gridded estimate for "all agricultural land (arable + intensively managed grassland)" available at 0.5° spatial resolution. To derive country and NUTS-level critical N surplus (in kg N yr^{-1}), these gridded estimates (kg N ha^{-1} yr^{-1}) were multiplied by total agricultural area (ha) of respective spatial unit and then aggregated spatially based on boundaries (country and NUTS-1). The same method was applied to derive a total value for EU-27 by aggregating across its constituent countries.

For actual N surplus, defined as the difference between total inputs (In) and outputs (Out) (Equations 3–5), we employed a high-resolution dataset (5 arcmin) developed by Batool et al. (2022)[15], which provides long-term, spatially consistent estimates of N inputs and N outputs calculated using a soil surface N budget. Inputs included synthetic fertilizers (Fert), animal manure (Man)(being equal to excreted manure corrected for gaseous emissions in housing and manure storage systems), atmospheric deposition (Dep), and biological N fixation (BNF). Outputs reflect N removed through harvested crops (Out_{crops}) and grazed or cut pasture (Out_{past}). We used these gridded estimates to derive the actual N surplus by multiplying them by the total agricultural area of each spatial unit and then aggregating them spatially based on boundaries (country and NUTS-1).

$$Surp(j,t) = In(j,t) - Out(j,t) \tag{3}$$

$$In(j,t) = In_{\text{Fert}}(j,t) + In_{\text{Man}}(j,t) + In_{\text{Dep}}(j,t) + In_{\text{BNF}}(j,t) \tag{4}$$

$$Out(j,t) = Out_{\text{crops}}(j,t) + Out_{\text{past}}(j,t) \tag{5}$$

where j is country or NUTS-region and t the time.

Fertilizer application was estimated from FAOSTAT (Food and Agriculture Organization Corporate Statistical Database)[37] and IFA (International Fertilizer Industry Association)[38] for 1961–2019. Gridded allocations were based on land-use data[39], using two alternative distribution methods to differentiate applications to croplands and pastures[40]. Manure in-

puts were estimated from two independent sources — FAOSTAT[41] and Einarsson et al. (2021)[40] — which differ in their approaches to livestock N excretion. Both were downscaled using gridded livestock distributions from Zhang et al. (2017)[42], with two separate methods used to apportion manure between cropland and pasture areas[40,43]. Further, the manure inputs in the soil N budget are considered after accounting for manure management and storage losses[15].

Atmospheric deposition was estimated from downscaled Chemistry-Climate Model Initiative (CCMI) outputs[44], and biological N fixation was calculated using standard crop- and pasture-specific rates[15]. Crop N removal was based on production data combined with crop-specific N content values. For pastures, N removal was estimated using NUE assumptions. Further, to account for uncertainty in underlying N surplus components, the N surplus dataset includes an ensemble of 16 surplus estimates by combining two fertilizer estimates, four manure methods, and two pasture NUE assumptions. In this study, the average of these 16 estimates was used as the final N surplus value for each region and year. Please refer to Batool et. al.[15] for more details on the underlying methodology to construct N surplus and its components.

We also evaluated ENMI outcomes using uncertainty bounds, defined as the mean of 16 N surplus estimates plus or minus one standard deviation (SD). The resulting upper- and lower-bound ENMI trajectories (Figs. S3–S4) show only minor deviations from the mean, confirming that the main patterns and overall conclusions remain robust.

N Yield Ratio

The N yield ratio ($R_{N_{yield}}$) quantifies the productivity dimension of the ENMI by comparing actual N output from agricultural systems to a region-specific N output or yield reference. It reflects how close a region is to achieving its productive potential.

The ratio is defined as:

$$R_{N_{\text{yield}}}(j,t) = \begin{cases} \frac{N_{\text{yield}}(j)}{N_{yield_{reference}}(j,t)}, & \text{if } \frac{N_{\text{yield}}(j)}{N_{yield_{reference}}(j,t)} \leq 1 \\ 1, & \text{if } \frac{N_{\text{yield}}(j)}{N_{yield_{reference}}(j,t)} > 1 \end{cases} \tag{6}$$

where j is the spatial unit (e.g., NUTS region) and t is the time. The numerator represents the actual N output from cropland and pasture, while the denominator is a region-specific reference yield set equal to attainable yield estimates[8] being comparable to target yields as explained below.

A value of 1 indicates that the region has reached or exceeded its reference productivity potential. Values below 1 indicate underperformance relative to the attainable reference value. Similar to the N surplus ratio, values above 1 are set to 1, because surpassing the reference means that the target crop yield has been reached.

In this study, reference N yields were based on values reported by Schulte-Uebbing et al. (2022)[8], who compiled region-specific estimates of attainable yields, actual yields,

and their ratio for cropland and intensively managed grassland. For cropland, Schulte-Uebbing et al. (2022)[8] derived attainable yields from the global assessment by Mueller et al. (2012)[45], who used a climate-binning approach: agricultural areas were grouped by annual precipitation and growing degree days, and the 95th percentile yield within each bin was used to represent attainable performance. This reflects the upper range of yields achieved under favorable conditions in each climatic zone. For grassland, Schulte-Uebbing et al. (2022)[8] used estimates from Rolinski et al. (2021)[46], who applied the LPJmL (Lund-Potsdam-Jena managed Land) model to simulate maximum livestock densities under local climate and soil conditions. These were converted to N uptake using an assumed feed demand of 4000 g C per LSU per day and a C:N ratio of 20:1, resulting in a N uptake equivalent of 73 kg N LSU^{-1} ha^{-1} yr^{-1}. Regional reference uptake was calculated by multiplying this value with modeled livestock densities, assuming a uniform feed demand per LSU, independent of milk production level or production system intensity. A safeguard was applied to ensure that the calculated maximum N uptake for each region did not fall below the N uptake estimated for 2010. It should be noted that the attainable yields derived by Mueller et al (2012)[45], used in this study, are reasonable comparable to target yields, which are defined as 80% of the water limited yield. This follows from a comparison of attainable yields as described above with water limited yields for wheat and barley, as derived by a much more detailed approach used in the Global Yield Gap Atlas (GYGA), which appear to be consistently higher[8].

We computed $N_{yield_{reference}}$ by multiplying our actual N outputs (averaged over the

2010s) to used with the region-specific yield potential ratios (yield potential / actual yield) as provided by Schulte-Uebbing et al. (2022)[8] according to:

- Western Europe: 1.18 (cropland), 1.04 (pasture)
- Central Europe: 1.98 (cropland), 1.31 (pasture)
- Turkey: 1.80 (cropland), 1.99 (pasture)
- Ukraine region: 2.63 (cropland), 1.64 (pasture)

In each NUTS region a ratio was based on the area of cropland or pasture using its the IMAGE region classification. This enabled normalization of N output in a way that is grounded in regional agronomic and biophysical conditions, but consistent across Europe.

Actual N yield (N_{yield}) is calculated as the total N removed annually from cropland and pasture through harvested crops and grazed or cut grass, respectively. The data is derived from Batool et al. (2022)[15], which provides N removal estimates at a 5 arcmin resolution. These were aggregated to the country or NUTS-1 level for use in ENMI calculations.

For cropland, N removal was estimated by multiplying crop production with crop-specific N content. Crop production data from 1961–2019 were sourced from FAOSTAT[47] and supplemented with fodder crop estimates from Einarsson et al. (2021)[40]. Country-level crop production was downscaled to grid level using the spatial distribution from Mon-

freda et al. (2008)[39], preserving subnational heterogeneity over time. N removal from pasture was estimated by multiplication of N inputs from manure and fertilizer with NUE approach, with NUE adjusted for losses following manure application. Two alternative scenarios for NUE and N losses were applied to capture uncertainty. In the first scenario, NUE of 0.6 was assumed based on Bouwman et al. (2005)[48] and a value of 0.2 for N losses based on FAOSTAT. In the second scenario, NUE value of 0.4 and 0.5 was assumed for the countries located in Eastern and Western Europe, respectively, based on NUE values reported by Kaltenegger et al. (2021)[49] and 0 for N losses. The total N output from cropland and pasture was then summed per region and used in the numerator of the N yield ratio (Equation 6).

Future Estimates of ENMI

To explore how nitrogen (N) management in Europe could evolve under different policy and practice trajectories, we developed three forward-looking scenarios for the year 2030. These scenarios build on a harmonized baseline data for agricultural N surplus and N output (2015–2019) and simulated changes based on projected adjustments in N inputs and their corresponding impacts on productivity.

Scenario Assumptions

The GD-F (Green Deal Fertilizer) scenario reflects a policy-aligned pathway in which fertilizer use is reduced by 20% by 2030, consistent with the nutrient loss reduction target outlined in the EU F2F Strategy[50].

The FAO-F (FAO Fertilizer) scenario is based on the "Towards Sustainability Scenario (TSS)" developed by FAOSTAT for high-income countries[51]. The TSS scenario includes a 43% reduction in synthetic fertilizer use relative to 2012, along with a 5% increase in agricultural production. In our analysis, we adopt the fertilizer reduction from TSS, while N outputs are determined using the TMPs (Technological and Management Practices) approach described below. This scenario reflects a broader transformation toward sustainable agriculture with gains in both productivity and environmental performance. The FAO-FM (FAO Fertilizer and Manure) scenario builds on FAO-F by also including a 4% reduction in manure inputs. This additional reduction corresponds to expected decreases in livestock production under the TSS scenario, and allows us to evaluate the combined impact of reducing both synthetic and organic N inputs.

These three scenarios were selected from the broader set of scenarios evaluated in an earlier study[9] because they represent both policy-relevant and globally recognized pathways. GD-F reflects the EU's Green Deal target, making it directly aligned with current European policy. FAO-F represents a mid-range transformation scenario developed

by FAOSTAT, while FAO-FM extends this by including manure reductions and was shown in an earlier study by Batool et al. (2025)[9] to achieve the strongest reductions in N surplus. Together, they span a gradient from moderate to ambitious interventions, providing a balanced set of futures for comparison.

Estimating N yield with technological improvements

To estimate future N yield (N_{output}) under changing input conditions, we used a one-parameter hyperbolic response function, commonly applied in agro-environmental studies to represent crop yield response to N availability[9,22,52]. This approach allows us to capture how TMPs influence the efficiency of N use.

$$Out(j,t) = \frac{c(j,t) \cdot In(j,t)}{c(j,t) + In(j,t)} \tag{7}$$

Here, j refers to the spatial unit (NUTS-1 or country), and t is the time. $In(j,t)$ and $Out(j,t)$ represent the N input and output, respectively, while $c(j,t)$ is the response coefficient that reflects the prevailing level of TMPs. All terms are expressed in kg N ha^{-1}yr^{-1}. Higher values of $c(j,t)$ indicate systems with greater potential to convert inputs into outputs under improved management.

To simulate future conditions, we assumed that TMPs continue to improve through 2030, following trends observed in the past. Consistent with the approach applied by

Batool et al. (2025)[9], we estimated $c(j,t)$ for each region using historical N input and output trajectories over eight periods between 1981 and 2019 (seven 5-year intervals and one final 4-year interval). We then extrapolated these $c(j,t)$ trends to 2030 using:

$$c(j,2030) = c_{\text{baseline}}(j) \cdot (1 + \Delta c_{\text{TMP}}(t)) \tag{8}$$

where $c_{\text{baseline}}(j)$ is the estimated coefficient from the 2015–2019 baseline, and $\Delta c_{\text{TMP}}(t)$ represents the advancement of TMPs projected to 2030. It is calculated from the historical rate of change in the response coefficient c multiplied by the time interval. In this way, $c(j,t)$ reflects the cumulative effect of continued TMPs improvement[9]. This implicitly account for aggregated improvements such as more efficient fertilizer use, better crop varieties, optimized timing, and advances in pasture management[22,23].

Using the scenario-specific projections of N input and the extrapolated $c(j,2030)$, we computed N output for each region. These estimates were then used to update the ENMI components: the N surplus ratio (using the projected N surplus in the denominator) and the N yield ratio (using the updated N output in the numerator). These values were combined to calculate ENMI enabling assessment of future regional performance under each scenario.

Data Availability

All datasets are publicly available on Zenodo. The main dataset used in this study is archived at https://doi.org/10.5281/zenodo.17226011[53].

Code Availability

The code used for data processing and analysis is available on Gitlab at:https://git.ufz.de/batool/n_surplus_enmi. Instructions for reproducing the results are provided in the accompanying README files.

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Author contributions

RK conceptualized the study with inputs from MB and SSG. MB conducted the analysis with inputs from RK. MB drafted the manuscript. All authors contributed to framing and revising the manuscript.

Competing Interests

The authors declare that they have no competing interests.

1. Sutton, M. *et al.* Our nutrient world: The challenge to produce more food and energy with less pollution. global overview of nutrient management. centre for ecology and hydrology, edinburgh on behalf of the global partnership on nutrient management and the international nitrogen initiative. *Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative* (2013).

2. De Vries, W. Impacts of nitrogen emissions on ecosystems and human health: A mini review. *Current Opinion in Environmental Science & Health* **21**, 100249 (2021).

3. De Vries, W. *et al.* Trends and geographic variation in adverse impacts of nitrogen use in europe on human health, climate, and ecosystems: A review. *Earth-Science Reviews* **253**, 104789 (2024).

4. Erisman, J. W. *et al.* Consequences of human modification of the global nitrogen cycle. *Philosophical Transactions of the Royal Society B: Biological Sciences* **368**, 20130116 (2013).

5. Chang, J. *et al.* Reconciling regional nitrogen boundaries with global food security. *Nature Food* **2**, 700–711 (2021).

6. European Commission: The European Green Deal, available at:. `https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52019DC0640&from=ET` (2019). Accessed: 20-03-2023.

7. European Commission: Sustainable development in the European Union – Monitoring report on progress towards the SDGs in an EU context – 2019 edition, available at:. https://data.europa.eu/doi/10.2785/44964 (2019).

8. Schulte-Uebbing, L. F., Beusen, A. H., Bouwman, A. F. & De Vries, W. From planetary to regional boundaries for agricultural nitrogen pollution. *Nature* **610**, 507–512 (2022).

9. Batool, M. *et al.* Scenario analysis of nitrogen surplus typologies in europe shows that a 20% fertilizer reduction may fall short of 2030 eu green deal goals. *Nature Food* **6**, 787–798 (2025).

10. Schulte-Uebbing, L. & de Vries, W. Reconciling food production and environmental boundaries for nitrogen in the european union. *Science of the Total Environment* **786**, 147427 (2021).

11. Billen, G. *et al.* Reshaping the European agro-food system and closing its nitrogen cycle: The potential of combining dietary change, agroecology, and circularity. *One Earth* **4**, 839–850 (2021).

12. Zhang, X. *et al.* Managing nitrogen for sustainable development. *Nature* **528**, 51–59 (2015).

13. Zhang, X. *et al.* Sustainable nitrogen management index: definition, global assessment and potential improvements. *Frontiers of Agricultural Science and Engineering* (2022).

14. De Vries, W., Kros, J., Kroeze, C. & Seitzinger, S. P. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. *Current Opinion in Environmental Sustainability* **5**, 392–402 (2013).

15. Batool, M. *et al.* Long-term annual soil nitrogen surplus across europe (1850–2019). *Scientific Data* **9**, 612 (2022).

16. Statistics Sweden, available at:. https://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/plant-nutrition-and-cultivation-measures/nitrogen-and-phosphorus-balances-for-agricultural-land-and-agricultural-pong/publications/nitrogen-and-phosphorus-balances-for-agricultural-land [Accessed: 09-July-2025].

17. European Commission. Nitrate directive 91/676/eec. https://eur-lex.europa.eu/eli/dir/1991/676/oj/eng (2000). [Accessed: 15-January-2024].

18. European Commission: Water Framework Directive, available at:. https://environment.ec.europa.eu/topics/water/water-framework-directive_en. [Accessed: 10-March-2024].

19. Sutton, M. A. *et al.* Too much of a good thing. *Nature* **472**, 159–161 (2011).

20. Maenhout, P. *et al.* Trade-offs and synergies of soil carbon sequestration: Addressing knowledge gaps related to soil management strategies. *European Journal of Soil Science* **75**, e13515 (2024).

21. Connor, D. J. Analysis of farming systems establishes the low productivity of organic agriculture and inadequacy as a global option for food supply. *npj Sustainable Agriculture* **2**, 2 (2024).

22. Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J. & Garnier, J. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environmental Research Letters* **9**, 105011 (2014).

23. Zhang, X., Mauzerall, D. L., Davidson, E. A., Kanter, D. R. & Cai, R. The economic and environmental consequences of implementing nitrogen-efficient technologies and management practices in agriculture. *Journal of Environmental Quality* **44**, 312–324 (2015).

24. Alexander, P. *et al.* High energy and fertilizer prices are more damaging than food export curtailment from ukraine and russia for food prices, health and the environment. *Nature Food* **4**, 84–95 (2023).

25. Rieger, J., Freund, F., Offermann, F., Geibel, I. & Gocht, A. From fork to farm: Impacts of more sustainable diets in the eu-27 on the agricultural sector. *Journal of Agricultural Economics* **74**, 764–784 (2023).

26. Hielkema, M. H. & Lund, T. B. Reducing meat consumption in meat-loving denmark: Exploring willingness, behavior, barriers and drivers. *Food Quality and Preference* **93**, 104257 (2021).

699 27. Billen, G. *et al.* Beyond the farm to fork strategy: Methodology for designing a euro-
700 pean agro-ecological future. *Science of the Total Environment* **908**, 168160 (2024).

701 28. Poikane, S. *et al.* Nutrient criteria for surface waters under the european water frame-
702 work directive: Current state-of-the-art, challenges and future outlook. *Science of the*
703 *total environment* **695**, 133888 (2019).

704 29. De Vries, W., Schulte-Uebbing, L., Kros, H., Voogd, J. C. & Louwagie, G. Spatially
705 explicit boundaries for agricultural nitrogen inputs in the european union to meet air
706 and water quality targets. *Science of the Total Environment* **786**, 147283 (2021).

707 30. Kaufmann, L. *et al.* Regional self-sufficiency: A multi-dimensional analysis relating
708 agricultural production and consumption in the european union. *Sustainable Produc-*
709 *tion and Consumption* **34**, 12–25 (2022).

710 31. Byrnes, D., Van Meter, K. & Basu, N. Long-term shifts in us nitrogen sources and
711 sinks revealed by the new trend-nitrogen data set (1930–2017). *Global Biogeochem-*
712 *ical Cycles* **34**, e2020GB006626 (2020).

713 32. Shi, T.-S. *et al.* A global meta-analysis on the effects of organic and inorganic fertil-
714 ization on grasslands and croplands. *Nature Communications* **15**, 3411 (2024).

715 33. 4 per 1000 Initiative. 4 per 1000 initiative. `https://4p1000.org` (2025). Accessed:
716 2025-10-02.

717 34. European Environment Agency. Water use and environmen-
718 tal pressures. `https://www.eea.europa.eu/themes/water/`

european-waters/water-use-and-environmental-pressures/water-use-and-environmental-pressures (2023). Accessed: 2025-08-26.

35. Schneider, K. R. *et al.* The state of food systems worldwide in the countdown to 2030. *Nature Food* **4**, 1090–1110 (2023).

36. Rockström, J. *et al.* A safe operating space for humanity. *nature* **461**, 472–475 (2009).

37. FAOSTAT (Food and Agriculture Organization Corporate Statistical Database): Fertilizer by nutrients, available at:. https://www.fao.org/faostat/en/#data/RFN. [Accessed: 10-October-2021].

38. Heffer, P., Gruère, A., Roberts, T. *et al.* Assessment of fertilizer use by crop at the global level. *International Fertilizer Industry Association, Paris* (2013).

39. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global biogeochemical cycles* **22** (2008).

40. Einarsson, R. *et al.* Crop production and nitrogen use in european cropland and grassland 1961–2019. *Scientific Data* **8**, 288 (2021).

41. FAOSTAT (Food and Agriculture Organization Corporate Statistical Database): Livestock Manure, available at:. https://www.fao.org/faostat/en/#data/EMN. [Accessed: 10-October-2021].

738 42. Zhang, B. *et al.* Global manure nitrogen production and application in cropland during
739 1860–2014: a 5 arcmin gridded global dataset for earth system modeling. *Earth*
740 *System Science Data* **9**, 667–678 (2017).

741 43. Tian, H. *et al.* The global n2o model intercomparison project. *Bulletin of the American*
742 *Meteorological Society* **99**, 1231–1251 (2018).

743 44. input4mips (input datasets for Model Intercomparison Projects): N deposition, avail-
744 able at:. https://esgf-node.llnl.gov/search/input4mips/. [Accessed:
745 10-July-2021].

746 45. Mueller, N. D. *et al.* Closing yield gaps through nutrient and water management.
747 *Nature* **490**, 254–257 (2012).

748 46. Rolinski, S. *et al.* Modeling vegetation and carbon dynamics of managed grasslands
749 at the global scale with lpjml 3.6. *Geoscientific Model Development* **11**, 429–451
750 (2018).

751 47. FAOSTAT (Food and Agriculture Organization Corporate Statistical Database): Crop
752 production quantity, available at:. https://www.fao.org/faostat/en/#data/
753 QCL. [Accessed: 10-August-2021].

754 48. Bouwman, A., Van Drecht, G. & Van der Hoek, K. Global and regional sur-
755 face nitrogen balances in intensive agricultural production systems for the period 1
756 $1/4$—$21/431/4$. *Pedosphere* **15**, 137–155 (2005).

757 49. Kaltenegger, K., Erb, K.-H., Matej, S. & Winiwarter, W. Gridded soil surface nitrogen
758 surplus on grazing and agricultural land: Impact of land use maps. *Environmental*
759 *Research Communications* **3**, 055003 (2021).

760 50. European Commission: Farm to fork strategy: for a fair, healthy and
761 environmentally-friendly food system, available at:. https://food.ec.europa.
762 eu/horizontal-topics/farm-fork-strategy_en. [Accessed: 10-January-
763 2024].

764 51. FAO (Food and Agriculture Organization of the United Nations): The Future of Food
765 and Agriculture—Alternative Pathways to 2050, available at:. http://www.fao.
766 org/3/I8429EN/i8429en.pdf. [Accessed: 10-March-2024].

767 52. Vishwakarma, S., Zhang, X. & Mueller, N. D. Projecting future nitrogen inputs: Are
768 we making the right assumptions? *Environmental Research Letters* **17** (2022).

769 53. Batool, M. *et al.* Enmi europe dataset. https://doi.org/10.5281/zenodo.
770 17226011 (2025).

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