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# Crop mix shapes the interpretation of national nitrogen use efficiency

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**Research Article**

**Keywords:**

**Posted Date:** November 12th, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-11117865/v1

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# Crop mix shapes the interpretation of national nitrogen use efficiency

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## Abstract

Nitrogen use efficiency (NUE) is widely used to track agricultural nitrogen management, with higher national values read as evidence for improvement. However, crops differ in nitrogen input requirements and nitrogen removal, so national NUE also depends on what countries grow and how crop mix changes over time. Using European data for 2000-2021, we hold crop mix at its baseline and recompute NUE to estimate the divergence associated with crop mix change. Accounting for crop mix changed the inferred direction of NUE progress in 10 countries, revealing cases where the reported improvements were largely associated with shifts in what was grown, as well as cases where declining NUE masked improvements under a fixed crop mix. Crop mix also affected cross-country benchmarking, substantially changing how many countries ranked against agronomically similar peers. We therefore propose a crop mix adjusted interpretation of national NUE, particularly when comparing countries, tracking progress or informing nitrogen targets. Doing so makes NUE more comparable and reduces the risk of attributing changes in cropping systems to nitrogen management.

## 1. Introduction

Nitrogen use efficiency (NUE) has become a scorecard for sustainable cropland nitrogen management. Calculated as the ratio of crop nitrogen (N) removed in harvested products to N inputs, it is used to assess whether production is becoming less nitrogen intensive, to compare national performance and to inform N targets (EU Nitrogen Expert Panel, 2015; Hutchings et al., 2020;

Lassaletta et al., 2016, 2014). At the national scale, higher NUE is commonly interpreted as evidence of improved N management, whereas lower NUE is often read as lower agronomic performance and greater potential losses.

This interpretation underpins its increasing use in agri-environmental monitoring and policy evaluation (Ludemann et al., 2024). However, it implicitly assumes that national crop mix remains sufficiently stable, or sufficiently irrelevant. Changes in NUE would then be caused mainly by changes in yields and N inputs. Indeed, crop mix has been recognized as a determinant of national NUE trajectories (Zhang et al., 2015), but the implications for interpreting national trends, comparing countries and setting NUE targets have not been systematically examined.

Interpreting national NUE trajectories only as changes in yields and N inputs becomes problematic when crop mix differs across countries or changes over time. Crops differ in harvested N removal, residue removal and input requirements (Coello et al., 2025; Ludemann et al., 2022), as well their residual effects on other crops grown in a cropping system. National NUE is therefore partly a crop mix weighted aggregate of crop-specific N flows. A country can increase the reported NUE by reallocating cropland towards crops associated with a higher apparent NUE (**Figure S1**), even if the yield-input performance in cropping system does not improve. Conversely, diversification towards crops with lower aggregate NUE may reduce the reported national NUE even when yields and N inputs improve under a fixed crop mix. National cropland NUE should therefore not be interpreted as a crop-agnostic indicator of agronomic performance. This distinction is illustrated conceptually in Figure 1, where the observed change in NUE is separated into changes under a fixed crop mix and the additional contribution associated with crop reallocation.

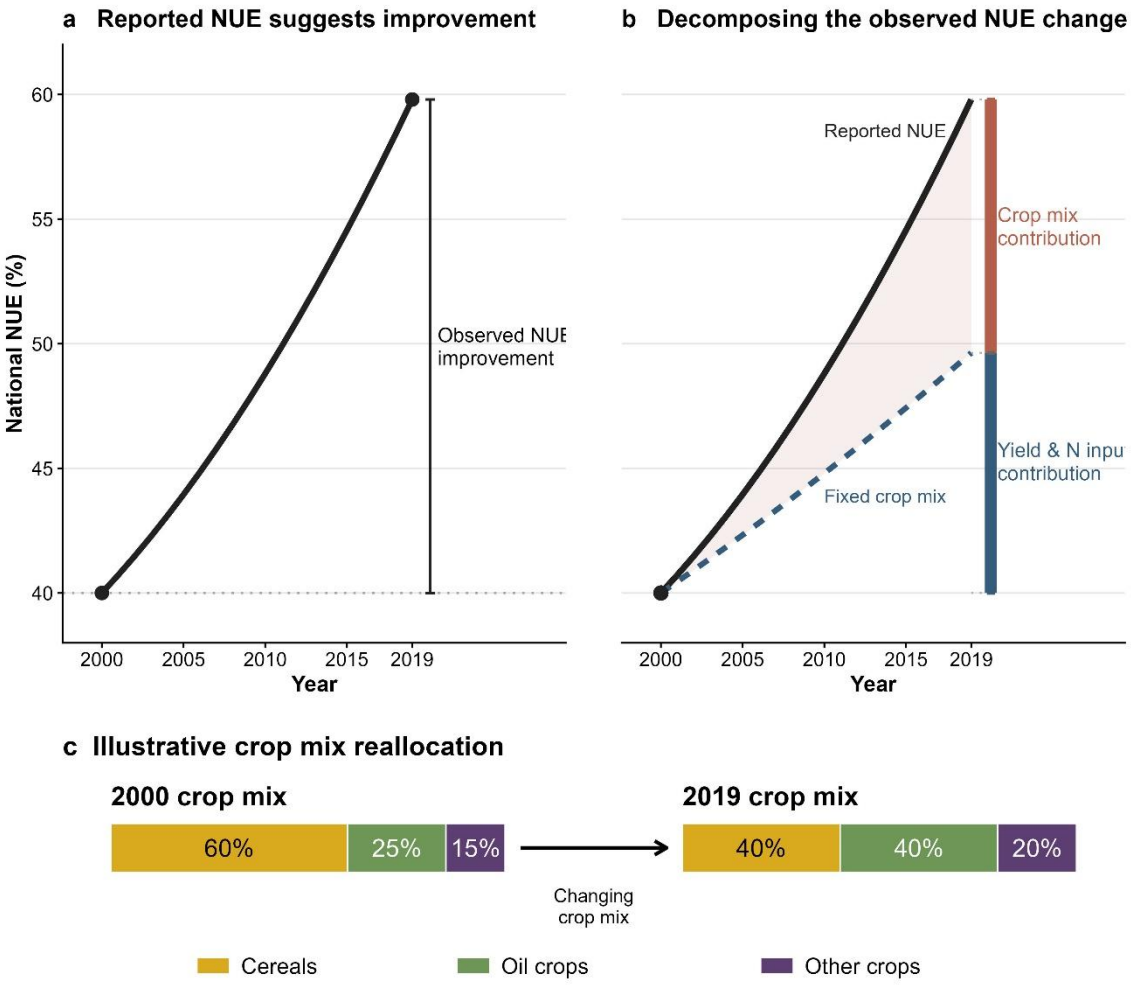



**Figure 1.** Conceptual framework for interpreting changes in national cropland NUE. (a) An increase in reported NUE is commonly interpreted as improved nitrogen performance. (b) When crop mix changes, the observed NUE change can be separated into the change occurring under a fixed crop mix, associated with changes in yields and nitrogen inputs, and an additional contribution associated with crop mix change. (c) Illustrative cropland reallocation showing how shifts in crop shares can generate a crop-mix contribution to national NUE. Values and crop shares are illustrative and do not represent a specific country.

This interpretation problem may matter even when crop mix is stable, because countries grow very different crops (Ghassemi et al., 2024). A country dominated by cereal production should not be benchmarked in the same way as one where permanent or horticultural crops occupy a large share of cropland. The problem becomes sharper when crop mix also changes over time. Such changes may come from agricultural restructuring, dietary and market shifts, environmental objectives and policy incentives (Leip et al., 2022; Meng et al., 2024) and geopolitical conflicts (Medinets et al., 2025), but they do not need to occur everywhere for crop mix to affect NUE comparability. As NUE is increasingly used to assess sustainability performance (Hutchings et al., 2020; Lassaletta et al., 2014;

Liu et al., 2025; Ludemann et al., 2024; van Ittersum et al., 2025) and policy progress (*FAO*, 2025), the reported national NUE may therefore combine changes in yields and N inputs with differences in what crops are grown. This complicates both cross-country benchmarking and the definition of realistic national NUE targets, which should reflect the crops that dominate national agriculture.

Here, we quantify how changes in crop mix, yields and N inputs jointly affect national cropland NUE trajectories across Europe from 2000 to 2021. We first examine how crop groups are associated with NUE across and within countries. We then use counterfactual analyses to estimate how national NUE trajectories would have evolved if crop mix had remained fixed. Finally, we develop a benchmarking approach in which countries are compared with countries sharing similar crop mixes. Building on previous guidance from the EU N Expert Panel for farm-level NUE (EU Nitrogen Expert Panel, 2015), we provide a practical framework for interpreting national NUE trajectories during food system transitions.

## 2. Methods

### 2.1. Data sources

We derived national data for European countries during 2000-2021 from FAOSTAT of crop areas and yields. We also collated N flows, specifically N inputs (sum of manure, mineral fertilizers, biological N fixation, atmospheric deposition and seeds), as well as N outputs (sum of N in harvested crop products and the N in crop residues removed from fields). All the derivations of crop N removal and crop residues conform to Ludemann et al. (2024) and Aramburu-Merlos et al. (2025), respectively.

### 2.2. Defining crop mix

Crop mix was here defined as the annual distribution of cropland area across crops, expressed as area shares ($C_{mix}$; %). $C_{mix}$ was derived by aggregating individual crops into 18 categories (Supplementary Methods), while key crops (e.g. maize, wheat, olives) were used individually. Temporary and permanent grasslands were not included in our analysis to ensure coherence with N flows data (Ludemann et al., 2024). For each year and country, we aggregated total area per crop group and calculated group-level yields as area-weighted averages of their component crops.

### 2.3. Decomposing the cropland N use efficiency

The cropland NUE is commonly derived as the ratio between cropland N outputs ($N_{Outputs}$) and total N inputs ($N_{Inputs}$). N outputs included the N removed in harvested crop products ($N_{yield}$) and the N removed in crop residues harvested from the field ($N_{res}$). N inputs included mineral fertilizers, manure, biological N fixation, atmospheric deposition and seeds. All terms are given in kg N $ha^{-1}$ $yr^{-1}$ unless specified.

$$NUE_{Reported} = \frac{N_{Outputs}}{N_{Inputs}} = \frac{N_{yield} + N_{res}}{N_{Inputs}} \quad (1)$$

$N_{Outputs}$ can be further decomposed as:

$$N_{Outputs,i} = N_{yield,i} + N_{res,i} = \sum_i A_i \cdot Y_i \cdot N_{crop,i} + A_i \cdot Y_i \cdot \left(\frac{1}{HI} - 1\right) \cdot f_{res,rem} * N_{residue,i} \quad (2)$$

where for the *i*th crop, A corresponds to the area (ha), Y the yield (kg ha$^{-1}$), $N_{crop}$ the N content of harvested product (%), HI the harvest index (-), $f_{res,rem}$ the fraction of the residues removed from the field (-) and $N_{residue}$ the N content of the residues (kg N kg$^{-1}$).

Replacing Eq. 2 in Eq. 1 gives:

$$NUE_{Reported} = \frac{\sum_i A_i \cdot Y_i \cdot N_{crop,i} + A_i \cdot Y_i \cdot \left(\frac{1}{HI} - 1\right) \cdot f_{res,rem} * N_{residue,i}}{N_{Inputs}} \quad (3)$$

Crop mix ($C_{mix}$; %) can be derived as the share of cropland occupied by the *i*th crop on the *y*th year:

$$A_{i,y} = C_{mix,i} \cdot A_{cropland} \quad (4)$$

where $A_{cropland}$ is the total cropland area (ha), corresponding to the sum of area for the 18 crop groups and where the sum of $C_{mix}$ must always equal one.

Introducing Eq. 4 in Eq. 3 makes $C_{mix}$ explicit, showing how cropland NUE is a weighted average of crop-specific N in crop products (including residues).

$$NUE_{Reported} = \frac{A_{cropland} \cdot (\sum_i C_{mix,i} \cdot Y_i \cdot N_{crop,i} + C_{mix,i} \cdot Y_i \cdot \left(\frac{1}{HI} - 1\right) \cdot f_{res,rem} * N_{residue,i})}{N_{Inputs}} \quad (5)$$

### 2.4. Quantifying the contribution of crop mix on cropland NUE

We quantified the component of national cropland NUE associated with changes in $C_{mix}$. We did this by fixing $C_{mix}$ values to a defined baseline for all crops simultaneously, while crop-specific yields and N inputs evolved according to the statistical records. By holding crop mix constant while allowing crop-specific N outputs and national N inputs to follow their observed trajectories, it estimates the differences associated with crop mix change under the reported input trajectories. It does not reconstruct the crop-specific input requirements that would have occurred under an alternative cropping system.

We defined the year 2000 as a common baseline since it provided broad data coverage across European countries while avoiding the most disruptive phase of agricultural restructuring experienced by post-socialist economies during the 1990s. This enabled the assessment of crop mix trajectories over a 21-year period.

For counterfactual analyses involving individual crop groups, only crops present in the baseline year within a given country were considered. Crop groups absent in the baseline year were excluded from crop-specific counterfactuals.

A crop mix-adjusted cropland NUE ($NUE_{Fixedmix}$; %) was then defined according to a fixed crop mix from 2000:

$$NUE_{Fixedmix} = \frac{A_{cropland} \cdot (\sum_i C_{mix,base,i} \cdot Y_i \cdot N_{crop,i} + C_{mix,base,i} \cdot Y_i \cdot \left(\frac{1}{HI} - 1\right) \cdot f_{res,rem} * N_{residue,i})}{N_{Inputs}} \quad (6)$$

We further re-based $NUE_{Fixedmix}$ such that it is equal to $NUE_{Reported}$ in the baseline year by subtracting the baseline year difference from the full timeseries. We then calculated the differences ($D_{mix}$; %) present in cropland NUE attributed to $C_{mix}$ as the difference of $NUE_{Fixedmix}$ and $NUE_{Reported}$:

$$D_{mix} = NUE_{Fixedmix} - NUE_{Reported} \quad (7)$$

If $D_{mix}$ is positive, the NUE under the fixed crop mix trajectory was higher than the reported NUE, meaning that the observed crop mix change reduced the reported NUE relative to the 2000 crop mix. Negative values indicate the opposite. $D_{mix}$ therefore reflects divergence over time due to changes in crop mix rather than to differences at baseline.

We decomposed the reported change in cropland NUE into the contributions of crop mix change and of changes in yields and N inputs. For each country, we fitted linear trends to both the reported NUE and the crop mix-adjusted NUE over 2000-2021 and multiplied each slope by the length of the period to obtain the total change in each. The change in $NUE_{Fixedmix}$, in which crop mix is held at its baseline, represents the contribution of yields and N inputs, since crop mix is held constant.

The crop mix contribution was then obtained as the difference between the total change in reported NUE and the change in the crop mix-adjusted NUE:

$$\Delta NUE_{Reported} = \Delta NUE_{Yield+input} + \Delta NUE_{Fixedmix} \quad (8)$$

where $\Delta NUE_{Yield+input}$ is the change in the crop mix adjusted NUE and $\Delta NUE_{fixedmix}$ is the residual attributable to crop mix change. We used trend-based changes rather than the difference between individual start and end years to reduce sensitivity to inter-annual variability in the baseline and final years.

### 2.5. Statistical analyses

We quantified the association between the reported NUE and the share of cropland under each crop group using Pearson's correlation coefficient over the period 2000-2021. We first calculated pooled

correlations across all country-year observations. To distinguish persistent differences among national cropping systems from temporal changes within countries, we then calculated within-country correlations after centring crop-group shares and $NUE_{Reported}$ around their respective country means. The corresponding p-values were adjusted for multiple comparisons using the Bonferroni correction.

We then ranked changes in national crop mix between 2000 and 2021:

$$Crop\ reallocation = \frac{1}{2}\sum_{i}\left|C_{i,2021} - C_{i,2000}\right| \quad (9)$$

where for the *i*th crop mix category, we calculated the absolute changes in the respective crop mix between 2021 and 2000. Importantly, since crop group shares sum to 100%, an increase in the share of one group necessarily implies a decrease in one or more others. Crop group correlations should therefore be interpreted as descriptive associations with a crop reallocation rather than crop-specific effects.

### 2.6. Benchmarking national NUE according to crop mix

To enable comparisons among countries with similar cropping systems, we clustered countries according to their crop mixes and trajectories. For each country, we calculated the mean cropland share of each crop group over 2000-2021 and the corresponding change in share between 2000 and 2021. Absent crop groups were assigned a share of zero. The two sets of variables were standardised separately and weighted equally before being combined.

We calculated Euclidean distances among countries and applied agglomerative hierarchical clustering using Ward's minimum-variance method. We evaluated solutions containing two to eight clusters using mean silhouette width and selected a four-cluster solution based on statistical separation and agronomic interpretability.

We then calculated each country's percentile rank according to its mean reported national NUE over 2000-2021 using two reference groups: all European countries and countries belonging to the same crop mix cluster. The difference between the within-cluster and all-country percentiles quantified the change in relative standing after accounting for broad differences in crop mix.

This benchmark was used as a complementary interpretive tool. It does not replace absolute NUE values, N surplus indicators or environmentally defined performance targets (e.g., nitrate leaching), but provides a way for comparing countries with contrasting cropping systems by accounting for crop mixes.

### 2.7. Sensitivity to the crop mix baseline year

To assess the sensitivity to the baseline year, we repeated the counterfactual analysis using alternative crop mix baselines from 1998, 1999, 2001 and 2002. For each alternative baseline year, crop group shares were fixed at their values in the selected year, while crop-specific yields and national N inputs followed their reported annual trajectories. The resulting $NUE_{Fixedmix}$ estimates were compared with those obtained using the primary 2000 baseline.

We then evaluated the impact of changing baseline years in both the magnitude, and the interpretation of the crop mix effect. First, for each country and alternative baseline, we calculated the mean difference in the estimated crop mix effect relative to the 2000 baseline estimate across the full-time series. Second, we assessed whether the qualitative interpretation of national NUE trends changed with the choice of baseline year. Countries were classified according to whether $NUE_{Reported}$ and $NUE_{Fixedmix}$ trends both increased, both declined, or differed in direction. This allowed us to determine whether cases in which crop mix adjustment altered the interpretation of national NUE trajectories were robust to the selected baseline year.

## 3. Results and discussion

### 3.1. Crop mix is correlated with national NUE

The share of cropland occupied by individual crop groups was correlated with national cropland NUE across Europe (**Figure 2a**).

When all country-year observations were analysed together, the strongest positive associations were for other oil crops (i.e., rapeseed, sunflower; $r = 0.56$) and cotton ($r = 0.51$). Weaker but significant positive associations for cereals, namely wheat, maize and soybeans ($r = 0.23$-$0.26$). Countries allocating more cropland to these groups tended to report higher NUE. Conversely, the strongest negative associations were for citrus fruits ($r = -0.59$), rice ($r = -0.55$) and tropical fruits ($r = -0.45$), with moderate negative associations for grapes and nuts ($r \approx -0.40$) and vegetables ($r = -0.36$). Countries and years with larger shares of these permanent and horticultural crops tended to report lower national NUE. Associations were weak or non-significant for olives, other cereals and, after correction for multiple comparisons, sugar crops and pulses.

However, this analysis also reflects differences in national cropping systems. We therefore quantified within-country associations by centring crop shares and cropland NUE around their respective country means (**Figure 2b**). As expected, the associations were generally weaker, but several relationships remained. Wheat ($r = 0.23$) and soybeans ($r = 0.19$) were weakly positively associated with NUE, whereas other fruits ($r = -0.22$), other cereals ($r = -0.18$) and roots and tubers ($r = -0.14$) were negatively associated with NUE. These relationships were significant after correction for multiple comparisons. Associations for the remaining crop groups were weak or non-significant.

Our analysis thus demonstrates that crop mix is associated with national NUE, both across countries and within countries over time. This supports the basis for the counterfactual analysis that follows: if crop groups differ systematically in their relationship to NUE, then changes in crop mix over time may affect national NUE trajectories even under a stable management.

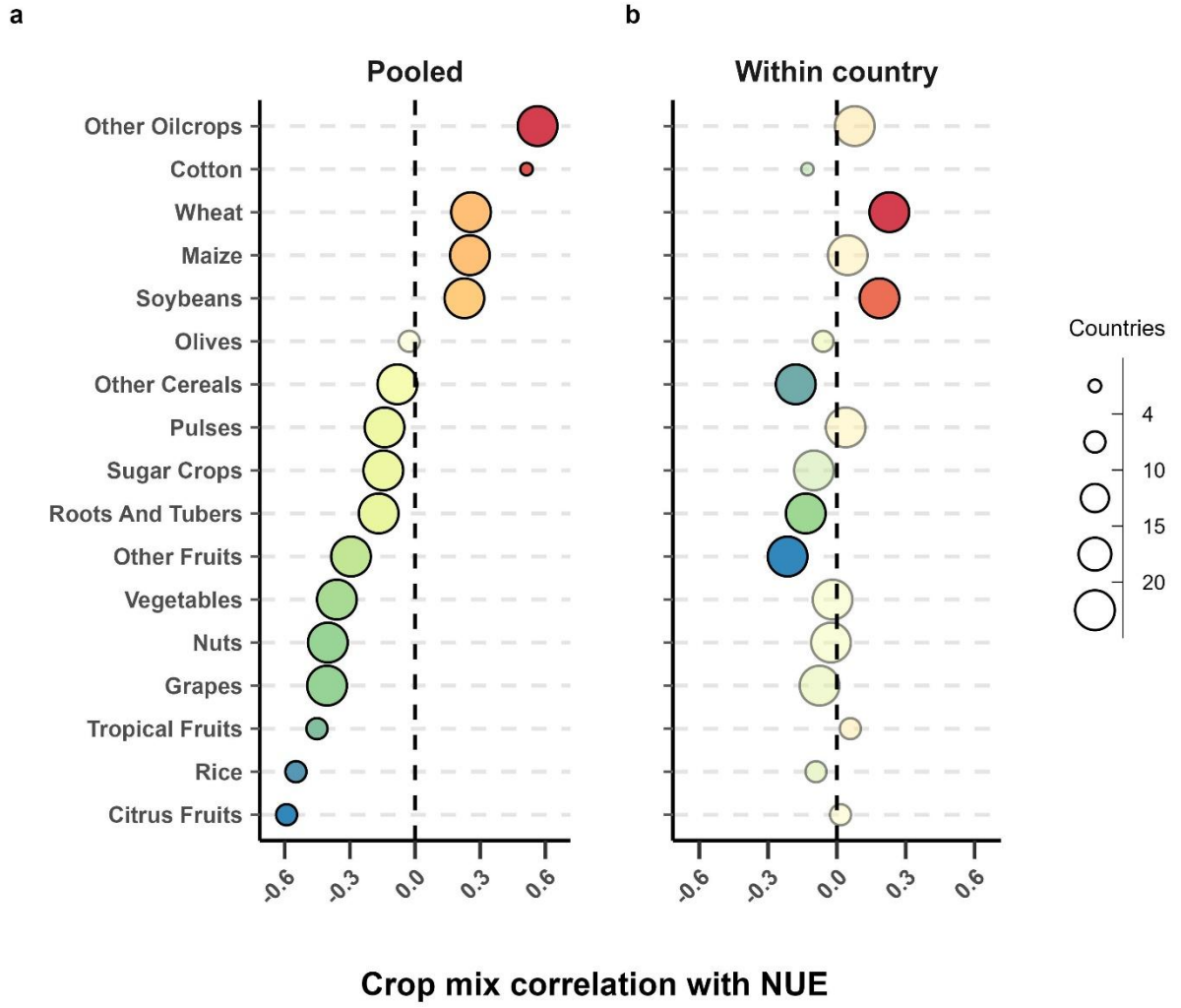



**Figure 2.** Associations between crop mix and the reported cropland NUE across European countries, 2000-2021. (a) Pearson correlations calculated across all country-year observations. Positive values indicate that countries and years with a larger share of a given crop group tended to have higher national NUE, whereas negative values indicate the opposite. (b) Within country Pearson correlations calculated after centring crop group shares and national NUE to their respective country means, thereby removing persistent differences in national cropping systems. Point size indicates the number of countries included for each crop group: positive values indicate that larger crop shares were associated with higher national NUE, whereas negative values indicate associations with lower national NUE. The strength and weakness of the correlation is denoted by point colour. Point transparency represents statistical significance after correcting for multiple comparisons: opaque points denote $p<0.05$ and transparent points denote non-significant associations.

### 3.2. Crop mix changed substantially across Europe

Crop mix changed substantially between 2000 and 2021 in Europe**,** but the changes were concentrated in a limited number of crop groups rather than evenly distributed across all crops (**Figure 3a**). In Eastern Europe, several countries, including Ukraine, moved away from other cereals, and roots and tubers, while increasing the share of wheat, other oil crops and maize. The Baltic countries (Latvia, Estonia and Lithuania) showed a similar pattern, unlike the more modest changes in the rest of Northern Europe. Southern Europe was more heterogeneous, with an increase in other cereals and permanent crops such as olives and nuts. Western European countries were generally the most stable, although several reduced the area allocated to other cereals.

These changes in the share of crops translated into widely different cropland reallocation across countries (**Figure 3b**). The crop-reallocation intensity ranged from less than 5% in the most stable countries (e.g., Denmark, France), to approximately 50% in the most dynamic countries (e.g., Serbia, Latvia). Most countries were within these extremes, with moderate to marked crop mix changes of 5-30%. The largest reallocations were concentrated in parts of Eastern, Northern and Southern Europe, while in Western Europe cropland reallocations were comparatively more stable.

The effect on the NUE depends on where these reallocations occur in the crop mix gradient (**Figure 2**). Shifts among crop groups with similar NUE associations (e.g., wheat to maize) should have a limited influence on the national NUE, whereas changes between groups at opposite ends of the gradient (e.g., fruits to oil crops) could change NUE even if N management did not change to the

same extent. We next test this directly by comparing the reported NUE with a fixed crop mix trajectory, isolating how much of the national NUE trend is associated with crop mix.

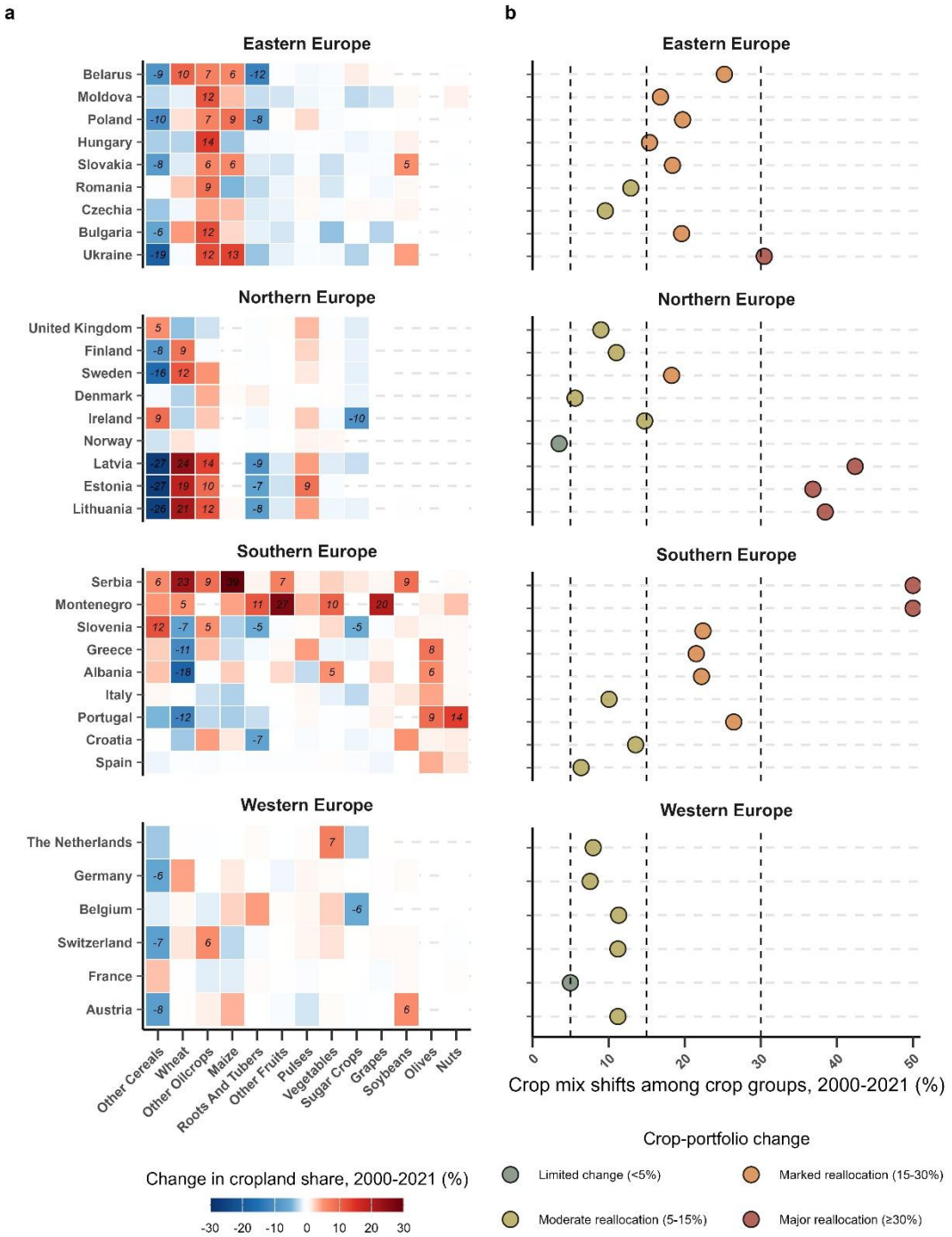



**Figure 3.** Crop mix changes across European cropland in 2000-2021. (a) Changes in the cropland share of major crop groups by country between 2000 and 2021. Colours indicate the changes in each crop group share; numeric labels are shown only for absolute changes above 5%. (b) Crop-reallocation intensity, calculate as half the sum of absolute changes in crop shares across all crop

groups. This represents the minimum share of cropland reallocated among crop groups. Countries are grouped by European region.

### 3.3. Crop mix changes NUE trajectories

By holding crop mix fixed at its 2000 baseline while allowing yields and N inputs to follow the reported trajectories, we estimated the difference between NUE with the fixed crop mix and the reported NUE (**Figure 4**). In this convention, positive values indicate that NUE under fixed crop mix trajectories was higher than the reported NUE, meaning that crop mix changes lowered the reported NUE relative to the 2000 crop mix. Negative values indicate that shifts in crop mix increased the reported NUE.

We found that the most pronounced negative effects occurred in Baltic states (Latvia, Lithuania, Estonia) and Eastern Europe (Ukraine, Bulgaria) (**Figure 4a**). In these countries, the reported NUE was 25-40% higher than under the baseline crop mix scenario, indicating that shifts in crop mix increased the apparent national NUE. These were the same countries that had the greatest crop mix changes (**Figure 3**), shifting away from crop groups associated with a lower NUE, such as other cereals and root crops, and towards groups associated with higher NUE, including wheat, maize, soybeans and oil crops (**Figures 2-3**).

More moderate positive effects were concentrated in parts of North- and Southern Europe, including Slovenia, Greece, Sweden and Finland, reaching +10-15%. In these countries, the crop mix counterfactual produced a higher NUE than the reported trajectory. Most Western EU countries, where crop mix changed less over time, showed effects close to zero (**Figure 4b**).

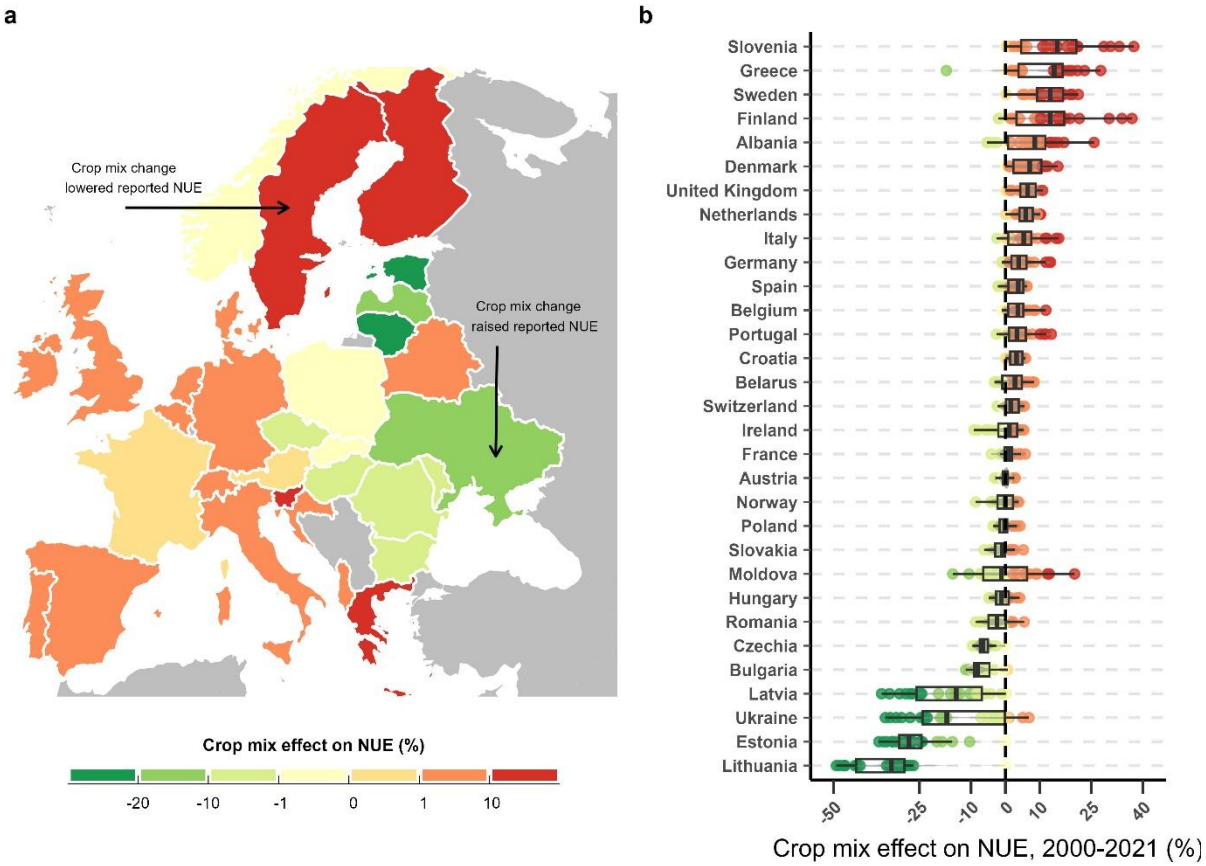



**Figure 4.** Difference between the NUE under the fixed crop mix trajectory using the year 2000 as baseline and the reported NUE across Europe during 2000-2021 ($D_{mix}$). The NUE under a fixed crop mix was NUE was calculated by holding crop mix at their 2000 values while crop-specific N outputs and national N inputs followed their reported annual trends. (a) Spatial distribution of the median $D_{mix}$ and (b) annual distribution of $D_{mix}$ for each country. Positive values indicate that the fixed trajectory produced a higher NUE than the reported trajectory, meaning that changes in crop mix reduced the reported NUE. Negative values indicate that reported NUE was higher than under the fixed crop-mix, meaning that changes in crop mix increased the reported NUE.

We next decomposed the reported change in national NUE between 2000 and 2021 into two contributions: the expected change under a fixed crop mix, reflecting the changes in crop-specific N outputs and national N inputs, and the residual component associated with crop mix shifts (**Figure 5**).

The clearest cases in which crop mix adjustments changed the interpretation were Latvia and Ukraine. In both countries, the reported NUE increased although the yield and input contribution was negative. Their apparent improvement was therefore attributable to the crop mix component. In Ukraine, this was mainly associated with declining shares of other cereals and increasing shares of maize, other oil crops and soybeans. In Latvia, the dominant contribution came from the shift away from other cereals and toward wheat, with smaller positive contributions from other oil crops (**Figure 3a, Figure S2**).

Estonia and Lithuania showed the same pattern as Latvia, with positive crop mix contributions mainly associated with declines in other cereals and increases in wheat and other oil crops (**Figure 3a, Figure S2**).

In most other countries the crop mix contribution was smaller, and the reported NUE change broadly reflected changes in yields and inputs. The largest crop mix effects generally occurred in countries with the greatest cropland shifts in crop mix (**Figure 3b**), showing that the reported NUE changes should not be interpreted only as changes in management without accounting for crop mix and other contextual factors, such as pedoclimatic conditions.

These patterns were also supported by a chained annual decomposition, which attributed yearly NUE changes symmetrically between crop mix changes and yield and input dynamics without relying on a single historical baseline (**Figures S3-4**; **Supplementary Methods**).

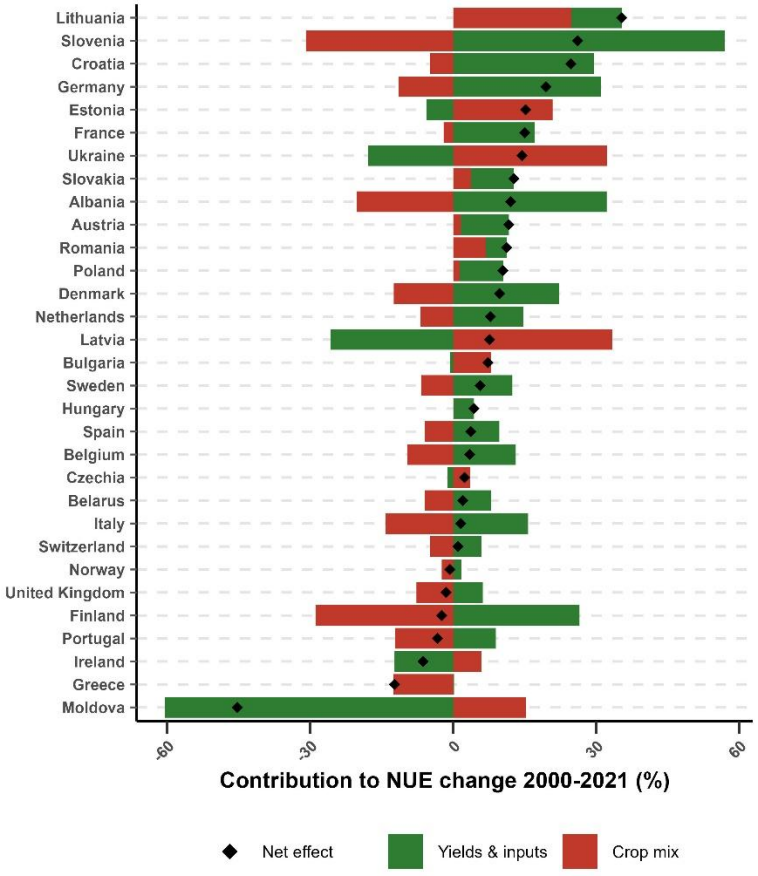



**Figure 5.** Contribution of crop mix change and yield and input dynamics to national cropland $NUE_{Reported}$ trends in Europe during 2000-2021. For each country, the $NUE_{Reported}$ change was decomposed into the contribution of changes in crop mix and the contribution of changes in crop-specific N outputs and N inputs under a fixed crop mix. The black diamond points denote the total calculated change in reported NUE. Positive values indicate contributions that increased the reported

NUE, whereas negative values indicate contributions that reduced it. Countries are ordered by their total $NUE_{Reported}$ change. Divergent contributions indicate cases in which shifts in crop mix either increased the apparent improvement or masked the changes associated with crop-specific N outputs and national N inputs.

### 3.4. Crop mix distorts the interpretation of NUE trends

Comparing the reported and the counterfactual NUE trends between 2000 and 2021 reveals how changes in crop mix changed not only the magnitude but the interpretation of national trends (**Figure 6**). We found that the reported NUE trajectories of most countries was lower than the fixed crop mix baseline (i.e., above the 1:1 line).

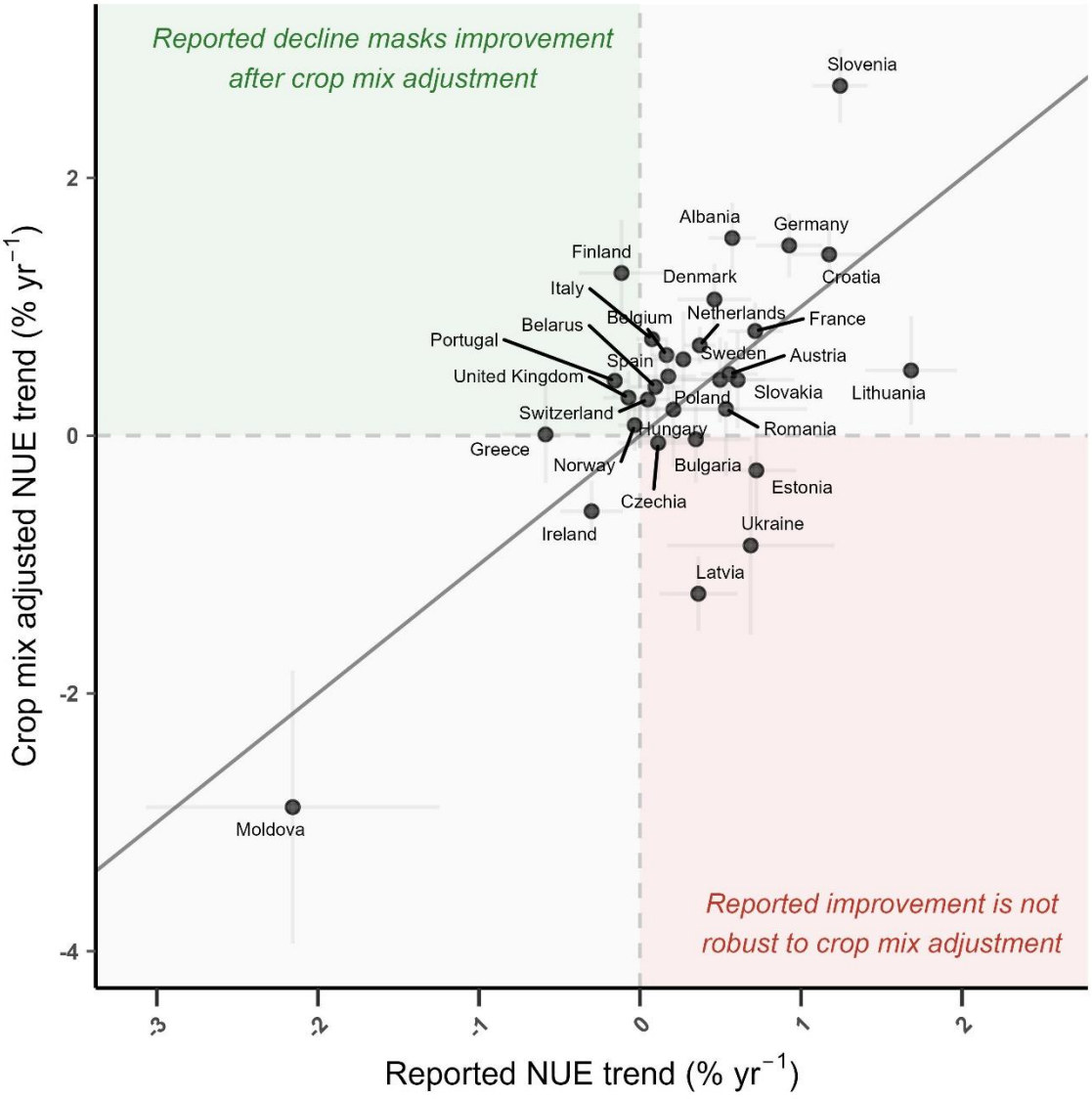
Adjusting crop mix changed the inferred direction of the NUE trend in several countries: increasing NUE trends were reported in 5 countries which showed a decreasing trend when using a fixed crop mix, while the opposite was also identified in 5 countries. For example, while Estonia, Ukraine and Latvia reported an improvement in the reported NUE, they showed flat or even declining crop mix adjusted trends (lower-right quadrant). Their apparent improvement was therefore not robust to changes in crop mix but rather may reflect a shift to crop groups associated with a higher "baseline" NUE. These are the same countries that experienced the largest structural changes in crop mix (**Figure 3**).

The opposite pattern was also observed, including in Finland and Portugal, where reported NUE declined while the crop mix adjusted trajectory improved. However, the different NUE approaches agreed in most countries although with different annual trends (top right quadrant in **Figure 6**).

The same reported NUE trend can therefore have different interpretations once crop mix is held constant. According to the reported NUE, several Eastern European countries would be credited with efficiency improvements, although these improvements were not robust to crop mix adjustments. Under the crop-mix adjusted NUE, this improvement disappears. Benchmarking or progress assessment based on the reported NUE alone may therefore misattribute crop transitions to management performance in precisely the countries experiencing the fastest food system changes.

Similarly to how it has been suggested to use companion indicators, such as the N surplus and minimum crop N yield requirements alongside with NUE to define the safe operation space for N, we recommend caution whenever NUE is being assessed across spatial and temporal scales, as well as benchmarked against other countries.

The interpretation of national NUE trends was generally robust to the choice of baseline year: our sensitivity analysis using alternative baseline years (1998-2002) produced similar qualitative classifications for most countries, including the main cases where crop mix adjustment changed the inferred NUE trend (**Figures S5-S6**).




352

353 **Figure 6.** Crop mix adjustment changes the interpretation of national cropland NUE trends across
354 Europe during 2000-2021. The reported NUE are compared with crop mix adjusted calculated with
355 fixed crop mix at their 2000 values. The horizontal and vertical error bars represent the slope standard
356 errors of the reported and crop mix-adjusted annual NUE trends, respectively. The dashed 1:1 line
357 represents identical trends under both approaches: countries above this line show stronger
358 improvement, or weaker decline, after adjusting for crop mix than under reported NUE, while
359 countries below the line show stronger improvement, or weaker decline, under the reported NUE than
360 after adjusting for crop mix. The shaded quadrants identify cases in which crop mix adjustment
361 changes the inferred direction of the national NUE trend.

### 3.5. Towards a fair benchmarking of cropland NUE

Direct cross-country comparisons of national NUE are affected by crop mix. The calculated $NUE_{Reported}$ reflects both yield-input performance and the mix of crops grown, implying that countries with contrasting cropping systems may not provide meaningful benchmarks for one another. A fairer comparison requires accounting for crop mix explicitly, which also implies that countries should have specific NUE targets that are based on their crop mix.

When countries are clustered according to the similarity of their mean crop mix over 2000-2021, it results into four interpretable clusters: a) cereal-dominated systems, b) intensive Northwestern European systems, c) Mediterranean and permanent-crop systems, and d) mixed Eastern European systems (**Figure 7**). Within each cluster, countries share broadly similar crop mixes, reducing one important source of heterogeneity in cross-country comparisons. Differences in NUE within clusters are therefore less likely to be dominated by crop mix effects, although they may still reflect differences in management, climate, soils and production intensity.

Benchmarking NUE within these crop mix clusters rather than across all of Europe changed national standings in both directions. When relative NUE rank was expressed on a 0-100 scale, where 0 denotes the lowest mean NUE and 100 the highest, benchmarking according to crop mix shifted countries by a median of 12 points. Seventeen of the 31 countries shifted by at least 10 points, with the largest upward shifts occurring in the Netherlands (+60), Italy (+48), Spain and Greece (+40 each), while the largest downward shifts occurred in Austria (-36), Hungary (-33), Bulgaria (-28) and Romania (-24).

Mediterranean countries generally ranked more favourably when compared with countries sharing similar crop mixes, indicating that their Europe-wide standing is partly influenced by the prevalence of permanent and horticultural crops. Conversely, several mixed Eastern European countries declined within their cluster, their Europe-wide standing overstating their efficiency relative to similar systems. High within-cluster standings in this group should be read with care, however: the trend decomposition (**Figure 5**) showed that the apparent NUE gains of countries such as Ukraine and Moldova were largely structural, so their favourable relative position should not be interpreted as evidence of a better N management, because it may also reflect crop mix differences and changing cropping systems.

Restricting comparisons to countries with similar crop mixes changed the benchmark against which national NUE performance was judged.

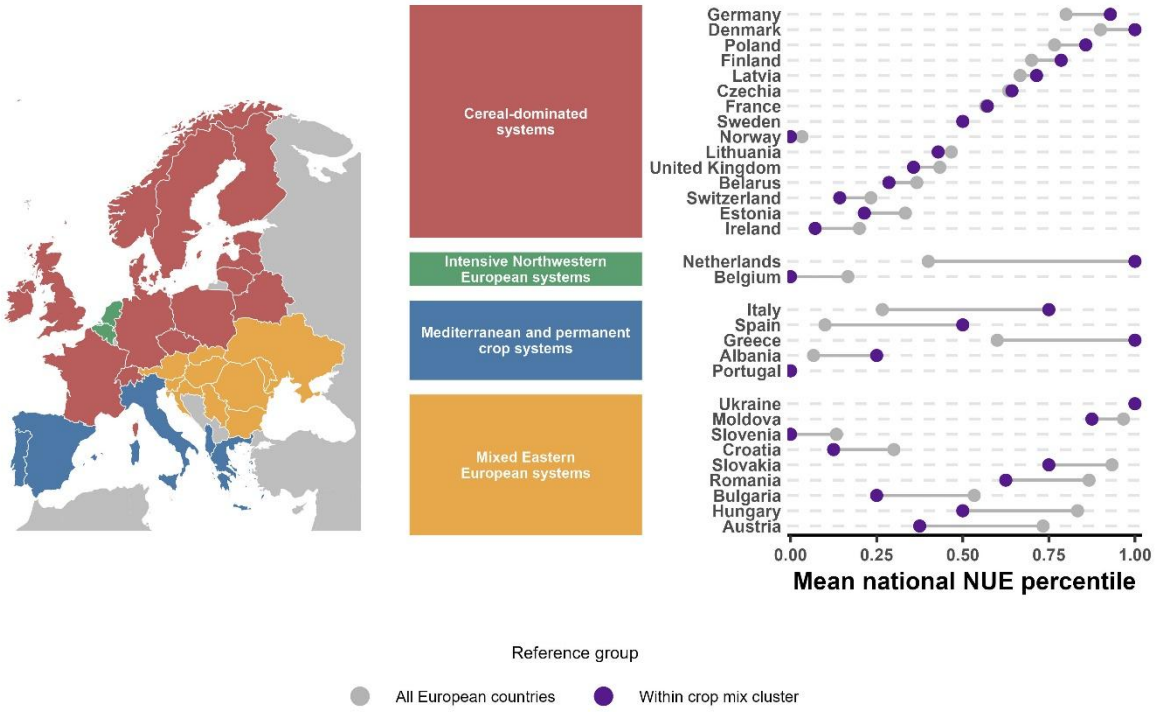



**Figure 7.** Comparison of national cropland NUE within crop mix clusters. Countries were grouped according to similarities in mean crop mix and crop mix change over 2000-2021. For each country, we calculated the mean reported cropland NUE over 2000-2021 and converted it into a relative rank, from 0 for the lowest mean NUE to 1 for the highest. Grey points show each country's relative rank among all European countries, while purple points show its relative ranks within each crop mix cluster. Connecting lines show the shift in relative standing when comparisons are restricted to countries with broadly similar crop portfolios. Rightward shifts indicate a higher percentile rank within the crop mix cluster than across all countries, whereas leftward shifts indicate a lower percentile rank within the cluster.

### 3.6. Implications for NUE benchmarking and indicator design

NUE remains a useful indicator for tracking N performance in cropland systems across Europe or other world regions. Its main value is that it condenses complex national N budgets into a simple metric that can be compared across countries and over time, ideally in conjunction with the N surplus as a key environmental indicator. Our results do not argue against the use of NUE but rather that cropland NUE becomes more informative when interpreted alongside changes in crop mix, especially in countries experiencing rapid agricultural restructuring or food system transitions.

For scientific assessments, reported NUE should therefore be complemented with a fixed crop mix trajectory. Holding crop mix constant provides a simple diagnostic test of whether the reported NUE trends are robust to changes in what is grown. Importantly, this does not replace the conventional

NUE reporting but rather separates two signals that otherwise can be misinterpreted: changes in yield-input performance under a fixed crop mix, and the changes associated with crop mix itself.

For policy benchmarking, countries should be compared against similar cropping systems. Direct cross-country comparisons can be misinterpreted due to the confounding effects of N performance with crop mix, particularly when countries have markedly different crop mixes in terms of cereals, oil seeds, permanent crops or horticultural systems. Crop mix clusters thus may provide a practical benchmarking complement, ensuring national comparisons are more interpretable when NUE is used to assess progress, set priorities or allocate responsibility.

Including a crop mix NUE interpretation should also remain tightly coupled with N surplus and other indicators of environmental losses. Adjusting for crop mix improves comparability, but it does not provide a direct measure of pollution. N surplus provides a complementary measure of potential environmental pressure, but it is itself influenced by crop mix through differences in N inputs and outputs. Adjusting NUE for crop mix therefore improves comparability but does not provide a direct measure of pollution. Indeed, a country can improve its apparent NUE performance via crop mix changes without necessarily reducing nitrate leaching, ammonia volatilisation or nitrous oxide emissions. National assessments should therefore combine NUE with N surplus, and where possible, indicators of these environmental losses.

Our proposed complementary analysis is diagnostic rather than causal, identifying the contribution associated with shifts in crop mix under reported country yield-input trajectories. Because national N budgets do not yet disaggregate crop-specific N inputs, the estimated crop mix contribution should be interpreted conservatively. Its value lies in preventing crop transitions from being mistaken for changes in N management, rather than attributing specific attribution mechanisms to individual crops.

## 4. Conclusions

National cropland NUE is not only shaped by changes in nitrogen inputs and crop nitrogen outputs, but also by changes in what crops are grown in a country. In Europe, shifts in crop mix changed the calculated national NUE trajectories and, in several countries, even changed the inferred direction of progress. The reported NUE trends can thus either overestimate improvements or mask yield-input gains when crop mix substantially changes over time.

NUE remains a valuable indicator for national nitrogen assessments, but it should not be interpreted as crop agnostic during food system transitions. Using fixed crop mix trajectories and benchmarking against similar cropping systems provide a practical complement to the conventional NUE reporting. When combined with the nitrogen surplus and other indicators of environmental losses, a crop mix interpretation can make national NUE assessments more comparable, more transparent and less prone to misattributing NUE changes due to crop transitions to nitrogen management. More broadly,

benchmarking NUE according to crop mix can support more realistic national NUE targets by distinguishing achievable improvements in N management from the differences associated with the structure of the agricultural sector in a country.

**Funding**

The European Nitrogen Expert Panel is supported by Fertilizers Europe. J. Serra also acknowledges support from the Pioneer Center for Research in Sustainable Agricultural Futures (Land-CRAFT), DNRF grant number P2, Aarhus University, Denmark and Agricultural nitrogen use efficiency platform (AgNUE) (Grant NNF25SA0112735). Views and opinions expressed are those of the authors only and do not necessarily reflect those of Fertilizers Europe, the European Commission or the granting authority.

**Conflicts of interest/Competing interests**

M. Q. serves as an Associate Editor of Agronomy for Sustainable Development.

**Consent to participate**

Not applicable.

**Consent for publication**

Not applicable.

**Ethics approval**

Not applicable.

**Data availability**

The datasets generated and analyzed during the current study are available in the FigShare repository, https://doi.org/10.6084/m9.figshare.33945886.

**Code availability**

The code used to generate and analyze the current study is available in the FigShare repository, https://doi.org/10.6084/m9.figshare.33945886.

**Author contribution**

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by João G. Serra. The first draft of the manuscript was written by João G. Serra and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**References**

Aramburu-Merlos, Fernando, Tenorio, Fatima, Lim, Ya Li, Carciochi, Walter, Dobermann, Achim, Grassini, Patricio, 2025. Global dataset on nutrient removal with crop residues.

Bodirsky, B.L., Beier, F., Humpenöder, F., Leip, D., Crawford, M.S., Chen, D.M.-C., von Jeetze, P., Springmann, M., Soergel, B., Nicholls, Z., Strefler, J., Lewis, J., Heinke, J., Müller, C., Karstens, K., Weindl, I., Stevanović, M., Rein, P., Sauer, P., Mishra, A., Bacca, E.J.M., Köberle, A.C., Wang, X., Singh, V., Hunecke, C., Collignon, Q., Schreinemachers, P., Dietz, S., Kanbur, R., Dietrich, J.P., Lotze-Campen, H., Popp, A., 2025. A food system transformation pathway reconciles 1.5 °C global warming with improved health, environment and social inclusion. Nat Food 6, 1133–1152. https://doi.org/10.1038/s43016-025-01268-y

Coello, F., Decorte, T., Janssens, I., Mortier, S., Sardans, J., Peñuelas, J., Verdonck, T., 2025. Global Crop-Specific Fertilization Dataset from 1961–2019. Sci Data 12, 40. https://doi.org/10.1038/s41597-024-04215-x

Coggins, S., McDonald, A.J., Silva, J.V., Urfels, A., Nayak, H.S., Sherpa, S.R., Jat, M.L., Jat, H.S., Krupnik, T., Kumar, V., Malik, R.K., Sapkota, T.B., Nayak, A.K., Craufurd, P., 2025. Data-driven strategies to improve nitrogen use efficiency of rice farming in South Asia. Nat Sustain 8, 22–33. https://doi.org/10.1038/s41893-024-01496-3

EU Nitrogen Expert Panel, 2015. Nitrogen Use Efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems. Wageningen University, Alterra, PO Box 47, NL-6700 Wageningen, Netherlands.

Ghassemi, B., Izquierdo-Verdiguier, E., Verhegghen, A., Yordanov, M., Lemoine, G., Moreno Martínez, Á., De Marchi, D., van der Velde, M., Vuolo, F., d'Andrimont, R., 2024. European Union crop map 2022: Earth observation's 10-meter dive into Europe's crop tapestry. Sci Data 11, 1048. https://doi.org/10.1038/s41597-024-03884-y

Hutchings, N.J., Sørensen, P., Cordovil, C.M. d. S., Leip, A., Amon, B., 2020. Measures to increase the nitrogen use efficiency of European agricultural production. Global Food Security 26, 100381. https://doi.org/10.1016/j.gfs.2020.100381

Lassaletta, L., Billen, G., Garnier, J., Bouwman, L., Velazquez, E., Mueller, N.D., Gerber, J.S., 2016. Nitrogen use in the global food system: past trends and future trajectories of agronomic performance, pollution, trade, and dietary demand. Environ. Res. Lett. 11, 095007. https://doi.org/10.1088/1748-9326/11/9/095007

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9, 105011. https://doi.org/10.1088/1748-9326/9/10/105011

Leip, A., Caldeira, C., Corrado, S., Hutchings, N.J., Lesschen, J.P., Schaap, M., de Vries, W., Westhoek, H., van Grinsven, H.JM., 2022. Halving nitrogen waste in the European Union food systems requires both dietary shifts and farm level actions. Global Food Security 35, 100648. https://doi.org/10.1016/j.gfs.2022.100648

Liu, J., Wang, H., Penuelas, J., Mou, J., Delgado-Baquerizo, M., Sardans, J., Coello, F., Quan, Z., Qiu, T., Li, Y., Guo, Y., Hu, Z., Ying, Y., Lv, J., Zhang, Y., Tan, W., Zhou, G., Li, L.-J., Fang, L.,

2025. Global-scale prevalence of low nutrient use efficiency across major crops. Nat Commun 16, 11036. https://doi.org/10.1038/s41467-025-66019-w

Ludemann, C.I., Hijbeek, R., van Loon, M., Murrell, T.S., Dobermann, A., van Ittersum, M., 2022. Global data on crop nutrient concentration and harvest indices. https://doi.org/10.5061/DRYAD.N2Z34TN0X

Ludemann, C.I., Wanner, N., Chivenge, P., Dobermann, A., Einarsson, R., Grassini, P., Gruere, A., Jackson, K., Lassaletta, L., Maggi, F., Obli-Laryea, G., Van Ittersum, M.K., Vishwakarma, S., Zhang, X., Tubiello, F.N., 2024. A global FAOSTAT reference database of cropland nutrient budgets and nutrient use efficiency (1961–2020): nitrogen, phosphorus and potassium. Earth Syst. Sci. Data 16, 525–541. https://doi.org/10.5194/essd-16-525-2024

Medinets, S., Oenema, O., Spears, B.M., Buyanovskiy, A., Medinets, V., Brownlie, W.J., Nemitz, E., Vieno, M., Sutton, M.A., 2025. Nutrient asymmetry challenges the sustainability of Ukrainian agriculture. Commun Earth Environ 6, 845. https://doi.org/10.1038/s43247-025-02826-9

Meng, B., Yang, Q., Mehrabi, Z., Wang, S., 2024. Larger nations benefit more than smaller nations from the stabilizing effects of crop diversity. Nat Food 5, 491–498. https://doi.org/10.1038/s43016-024-00992-1

OECD, 2025. Environmental Performance of Agriculture in OECD Countries: Key Trends and Insights [WWW Document]. OECD. https://doi.org/10.1787/2679ba38-en

Sustainable nitrogen management in agrifood systems, 2025. . FAO. https://doi.org/10.4060/cd3388en

van Ittersum, M.K., Silva, J.V., Bommarco, R., Hijbeek, R., Lundin, O., Nandillon, R., Bergkvist, G., Menegat, A., Öborn, I., Söderholm-Emas, A., Stoddard, F.L., Vico, G., Vonk, W.J., Watson, C.A., MacLaren, C., 2025. Narrowing the ecological yield gap to sustain crop yields with less inputs. Global Food Security 45, 100857. https://doi.org/10.1016/j.gfs.2025.100857

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528, 51–59. https://doi.org/10.1038/nature15743

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