

SUSTAINABLE NITROGEN MANAGEMENT INDEX: DEFINITION, GLOBAL ASSESSMENT AND POTENTIAL IMPROVEMENTS

Xin ZHANG (✉)¹, Yanyu WANG¹, Lena SCHULTE-UEBBING^{2,3}, Wim DE VRIES², Tan ZOU¹, Eric A. DAVIDSON¹

1 University of Maryland Center for Environmental Science, Frostburg, Maryland, 21532, USA.

2 Environmental Systems Analysis Group, Wageningen University & Research, Wageningen, 6708 PB, the Netherlands.

3 PBL Netherlands Environmental Assessment Agency, The Hague, 2594 AV, the Netherlands.

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Correspondence: xin.zhang@umces.edu

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SUPPLEMENTARY MATERIALS

Table S1 The SNMI score and its ranking, average NUE, average annual yield-N, and average annual total crop production-N for all countries during 2014–2018

Rank	Country/Region	SNMI score	NUE	Yield (kg ha ⁻¹ N)	Production (Tg N)
1	Argentina	0.28	0.72	102	4.1
2	Paraguay	0.34	0.66	138	6.6 × 10 ⁻¹
3	Tajikistan	0.40	0.73	64	5.5 × 10 ⁻²
4	Nepal	0.41	0.63	75	1.7 × 10 ⁻¹
5	Brazil	0.43	0.57	136	8.6
6	Ukraine	0.44	0.85	53	1.8
7	Serbia	0.45	0.61	71	2.0 × 10 ⁻¹
8	Saint Vincent and the Grenadines	0.46	1.12	50	2.5 × 10 ⁻⁴
9	Romania	0.46	0.74	55	5.0 × 10 ⁻¹
10	United States of America	0.47	0.54	86	14
11	Lao People's Democratic Republic	0.47	0.97	48	8.6 × 10 ⁻²
12	Hungary	0.47	0.59	69	3.1 × 10 ⁻¹
13	Denmark	0.52	0.50	85	2.1 × 10 ⁻¹
14	Malaysia	0.52	0.68	54	4.4 × 10 ⁻¹
15	Myanmar	0.52	0.65	56	6.9 × 10 ⁻¹
16	Bangladesh	0.52	0.48	99	8.5 × 10 ⁻¹
17	Bulgaria	0.53	0.56	63	2.3 × 10 ⁻¹
18	Slovakia	0.56	0.52	65	8.9 × 10 ⁻²
19	Greece	0.56	0.64	52	1.7 × 10 ⁻¹
20	Uruguay	0.57	0.46	85	1.8 × 10 ⁻¹
21	Cambodia	0.57	0.83	42	1.7 × 10 ⁻¹
22	Croatia	0.59	0.46	71	6.4 × 10 ⁻²

23	Bolivia (Plurinational State of)	0.59	0.61	50	2.3×10^{-1}
24	Republic of Moldova	0.59	0.82	40	7.8×10^{-2}
25	France	0.60	0.43	76	1.5
26	Democratic People's Republic of Korea	0.60	1.33	45	1.2×10^{-1}
27	Turkmenistan	0.60	0.82	38	7.7×10^{-2}
28	Austria	0.60	0.42	76	1.1×10^{-1}
29	Egypt	0.61	0.39	138	5.2×10^{-1}
30	Philippines	0.61	0.61	47	5.2×10^{-1}
31	Lithuania	0.62	0.52	55	1.2×10^{-1}
32	Germany	0.63	0.38	84	1.0
33	Rwanda	0.63	0.83	36	5.0×10^{-2}
34	Uzbekistan	0.64	0.37	85	3.8×10^{-1}
35	Latvia	0.65	0.55	47	6.0×10^{-2}
36	Mali	0.66	1.03	32	2.1×10^{-1}
37	Indonesia	0.66	0.55	47	2.3
38	Turkey	0.66	0.55	46	1.1
39	Czechia	0.67	0.37	69	1.7×10^{-1}
40	Viet Nam	0.67	0.37	68	7.6×10^{-1}
41	China	0.68	0.32	94	1.3
42	Tonga	0.68	1.02	29	8.8×10^{-4}
43	United Kingdom of Great Britain and Northern Ireland	0.68	0.32	87	5.3×10^{-1}
44	Guatemala	0.69	0.42	56	1.1×10^{-1}
45	Dominican Republic	0.70	0.99	27	1.4×10^{-1}
46	Nauru	0.71	0.64	35	1.4×10^{-5}
47	Azerbaijan	0.72	0.68	33	7.4×10^{-2}
48	Cook Islands	0.72	0.38	57	8.6×10^{-5}
49	Belize	0.73	0.38	56	6.7×10^{-3}
50	Kyrgyzstan	0.73	0.62	35	4.7×10^{-2}
51	Malawi	0.73	0.60	35	1.3×10^{-1}
52	Suriname	0.73	0.34	62	4.3×10^{-3}
53	Mauritius	0.74	0.40	51	4.1×10^{-3}
54	Estonia	0.74	0.49	42	2.8×10^{-2}
55	Ghana	0.75	0.97	23	1.7×10^{-1}
56	Italy	0.75	0.39	51	4.7×10^{-1}
57	Bhutan	0.75	0.59	33	3.5×10^{-3}
58	Benin	0.75	1.05	24	8.2×10^{-2}
59	Canada	0.76	0.44	44	1.7
60	Samoa	0.76	0.91	22	1.4×10^{-3}
61	Republic of Korea	0.76	0.29	66	1.1×10^{-1}
62	Belgium	0.76	0.24	95	8.1×10^{-2}
63	Madagascar	0.76	1.01	22	8.0×10^{-2}
64	Morocco	0.76	0.75	26	2.3×10^{-1}
65	Russian Federation	0.76	0.78	24	3.0
66	Sweden	0.77	0.41	46	1.2×10^{-1}
67	Grenada	0.77	1.09	31	2.2×10^{-4}
68	Australia	0.78	0.56	32	1.0
69	India	0.78	0.34	52	8.7
70	Lebanon	0.78	0.39	45	1.2×10^{-2}
71	Burundi	0.79	0.78	22	3.4×10^{-2}
72	Sri Lanka	0.79	0.52	36	8.3×10^{-2}
73	Guyana	0.79	0.74	29	1.4×10^{-2}
74	Cameroon	0.79	0.83	21	1.6×10^{-1}
75	United Republic of Tanzania	0.79	0.84	20	3.2×10^{-1}
76	Mexico	0.80	0.47	37	9.0×10^{-1}
77	Japan	0.80	0.35	48	2.1×10^{-1}
78	Costa Rica	0.81	0.26	61	3.4×10^{-2}

79	Iran (Islamic Republic of)	0.81	0.51	32	5.3×10^{-1}
80	Papua New Guinea	0.82	0.63	25	2.5×10^{-2}
81	Uganda	0.82	0.77	19	1.7×10^{-1}
82	Kazakhstan	0.82	0.92	16	4.9×10^{-1}
83	Chile	0.83	0.25	58	1.0×10^{-1}
84	Guam	0.83	1.22	18	1.8×10^{-4}
85	Jamaica	0.84	0.53	28	6.0×10^{-3}
86	Peru	0.84	0.42	36	1.7×10^{-1}
87	Kenya	0.84	0.61	24	1.5×10^{-1}
88	Poland	0.84	0.31	46	5.2×10^{-1}
89	Ethiopia	0.84	0.57	25	4.3×10^{-1}
90	South Africa	0.85	0.52	27	3.4×10^{-1}
91	Guinea	0.85	0.83	16	6.1×10^{-2}
92	Democratic Republic of the Congo	0.85	1.13	15	2.0×10^{-1}
93	Algeria	0.85	0.90	15	1.3×10^{-1}
94	Haiti	0.85	0.66	20	2.7×10^{-2}
95	North Macedonia	0.85	0.41	35	1.6×10^{-2}
96	Thailand	0.86	0.39	36	7.7×10^{-1}
97	Finland	0.86	0.39	36	8.0×10^{-2}
98	Ecuador	0.86	0.35	39	9.6×10^{-2}
99	Angola	0.87	0.71	17	8.6×10^{-2}
100	Burkina Faso	0.87	0.62	20	1.2×10^{-1}
101	Djibouti	0.87	0.18	64	1.3×10^{-4}
102	Nigeria	0.87	0.64	19	7.5×10^{-1}
103	Micronesia (Federated States of)	0.88	0.74	15	2.8×10^{-4}
104	Spain	0.88	0.36	36	6.1×10^{-1}
105	Sierra Leone	0.88	1.12	12	2.2×10^{-2}
106	Cuba	0.88	0.55	22	7.7×10^{-2}
107	Vanuatu	0.88	1.14	15	2.1×10^{-3}
108	French Guyana	0.89	1.40	19	3.6×10^{-4}
109	Togo	0.89	0.78	13	3.7×10^{-2}
110	Switzerland	0.89	0.19	57	2.4×10^{-2}
111	French Polynesia	0.89	0.61	18	4.5×10^{-4}
112	Sao Tome and Principe	0.89	0.73	15	6.2×10^{-4}
113	Netherlands	0.90	0.13	69	7.4×10^{-2}
114	Congo	0.91	0.77	11	6.9×10^{-3}
115	Ireland	0.91	0.09	118	5.4×10^{-2}
116	Iraq	0.91	0.66	18	9.7×10^{-2}
117	Slovenia	0.91	0.22	47	1.1×10^{-2}
118	Mozambique	0.91	0.76	11	6.4×10^{-2}
119	Colombia	0.92	0.24	47	2.3×10^{-1}
120	Equatorial Guinea	0.92	0.94	7	1.3×10^{-3}
121	Pakistan	0.92	0.27	40	1.2
122	El Salvador	0.93	0.35	31	2.8×10^{-2}
123	Timor-Leste	0.94	0.54	16	3.7×10^{-3}
124	Liberia	0.94	0.67	11	7.4×10^{-3}
125	Syrian Arab Republic	0.94	1.32	14	8.1×10^{-2}
126	Puerto Rico	0.95	0.31	31	2.2×10^{-3}
127	Yemen	0.95	0.60	13	1.9×10^{-2}
128	Kuwait	0.96	0.11	59	8.7×10^{-4}
129	Israel	0.97	0.24	36	1.5×10^{-2}
130	Martinique	0.98	1.86	48	8.0×10^{-4}
131	Malta	0.99	0.14	46	4.7×10^{-4}
132	Belarus	0.99	0.26	30	1.7×10^{-1}
133	Niger	1.00	0.60	8	1.4×10^{-1}
134	Luxembourg	1.00	0.13	46	2.9×10^{-3}
135	Mauritania	1.00	0.47	14	5.6×10^{-3}

136	Tunisia	1.00	0.51	12	5.8×10^{-2}
137	Chad	1.00	0.50	12	6.2×10^{-2}
138	Gambia	1.00	0.55	10	4.3×10^{-3}
139	Niue	1.01	0.70	4	1.5×10^{-5}
140	Jordan	1.01	0.29	26	7.8×10^{-3}
141	Honduras	1.01	0.29	25	4.0×10^{-2}
142	Afghanistan	1.02	0.42	15	1.2×10^{-1}
143	Norway	1.03	0.18	34	2.7×10^{-2}
144	Zambia	1.04	0.32	20	7.6×10^{-2}
145	Panama	1.04	0.36	16	1.2×10^{-2}
146	Albania	1.05	0.23	25	1.7×10^{-2}
147	New Zealand	1.06	0.06	47	2.7×10^{-2}
148	Maldives	1.07	0.29	19	1.3×10^{-4}
149	Dominica	1.07	0.41	10	2.4×10^{-4}
150	Armenia	1.07	0.17	29	1.4×10^{-2}
151	Fiji	1.08	0.37	11	2.9×10^{-3}
152	Nicaragua	1.08	0.26	19	3.3×10^{-2}
153	Oman	1.08	0.19	25	2.2×10^{-3}
154	Montenegro	1.09	0.08	38	5.3×10^{-4}
155	Senegal	1.09	0.35	11	3.7×10^{-2}
156	Guinea-Bissau	1.10	0.38	9	4.8×10^{-3}
157	Lesotho	1.11	0.41	6	2.0×10^{-3}
158	Venezuela (Bolivarian Republic of)	1.12	0.17	22	7.4×10^{-2}
159	New Caledonia	1.12	0.17	23	2.2×10^{-4}
160	Libya	1.12	0.37	6	1.3×10^{-2}
161	Gabon	1.12	0.34	8	4.2×10^{-3}
162	Guadeloupe	1.13	1.95	36	9.2×10^{-4}
163	Bosnia and Herzegovina	1.13	0.18	21	2.3×10^{-2}
164	Portugal	1.13	0.17	20	3.6×10^{-2}
165	Bahamas	1.14	0.17	20	2.5×10^{-4}
166	Zimbabwe	1.14	0.33	8	3.1×10^{-2}
167	Eritrea	1.15	0.32	7	4.8×10^{-3}
168	Sudan	1.15	0.31	7	1.5×10^{-1}
169	Tokelau	1.16	2.71	37	2.2×10^{-5}
170	Eswatini	1.16	2.13	37	7.1×10^{-3}
171	Georgia	1.16	0.15	19	8.5×10^{-3}
172	Solomon Islands	1.17	7.32	35	3.7×10^{-3}
173	South Sudan	1.20	0.26	5	1.5×10^{-2}
174	Barbados	1.20	0.09	20	1.7×10^{-4}
175	Cyprus	1.22	0.12	14	1.6×10^{-3}
176	Seychelles	1.22	0.13	12	1.9×10^{-5}
177	Palestine	1.23	3.89	25	4.1×10^{-3}
178	Kiribati	1.23	2.18	25	8.6×10^{-4}
179	Singapore	1.24	0.02	23	1.5×10^{-5}
180	Saudi Arabia	1.24	0.15	9	3.2×10^{-2}
181	Saint Lucia	1.25	0.11	11	1.1×10^{-4}
182	Somalia	1.25	0.18	5	5.1×10^{-3}
183	Cabo Verde	1.26	0.17	5	2.7×10^{-4}
184	Central African Republic	1.29	0.14	3	6.2×10^{-3}
185	Marshall Islands	1.30	7.95	15	1.3×10^{-4}
186	Antigua and Barbuda	1.31	0.09	5	2.5×10^{-5}
187	Namibia	1.31	0.11	3	2.5×10^{-3}
188	United Arab Emirates	1.32	0.04	9	7.3×10^{-4}
189	Trinidad and Tobago	1.32	0.03	10	4.6×10^{-4}
190	Tuvalu	1.32	0.08	5	8.7×10^{-6}
191	Saint Kitts and Nevis	1.32	0.09	3	1.7×10^{-5}
192	Mongolia	1.33	0.05	7	8.6×10^{-3}
193	Comoros	1.33	3.25	11	1.3×10^{-3}

194	Qatar	1.34	0.04	6	1.0×10^{-4}
195	Bahrain	1.34	0.04	5	2.5×10^{-5}
196	Brunei Darussalam	1.37	0.01	5	5.3×10^{-5}
197	Botswana	1.38	0.02	2	5.9×10^{-4}
198	Faroe Islands	1.39	0.02	2	4.6×10^{-6}
199	Iceland	1.40	0.01	1	1.5×10^{-4}

Note: The SNMI value for Dominican Republic was calculated based on the NUE and N yield data developed based on Zhang et al., 2015^[1]. Because the FAO nutrient budget database shows a dramatic increase in N yield for Dominican Republic, which is different from all other databases compared in Zhang et al., 2021 and suggests a potential error in the FAO nutrient budget database^[2].

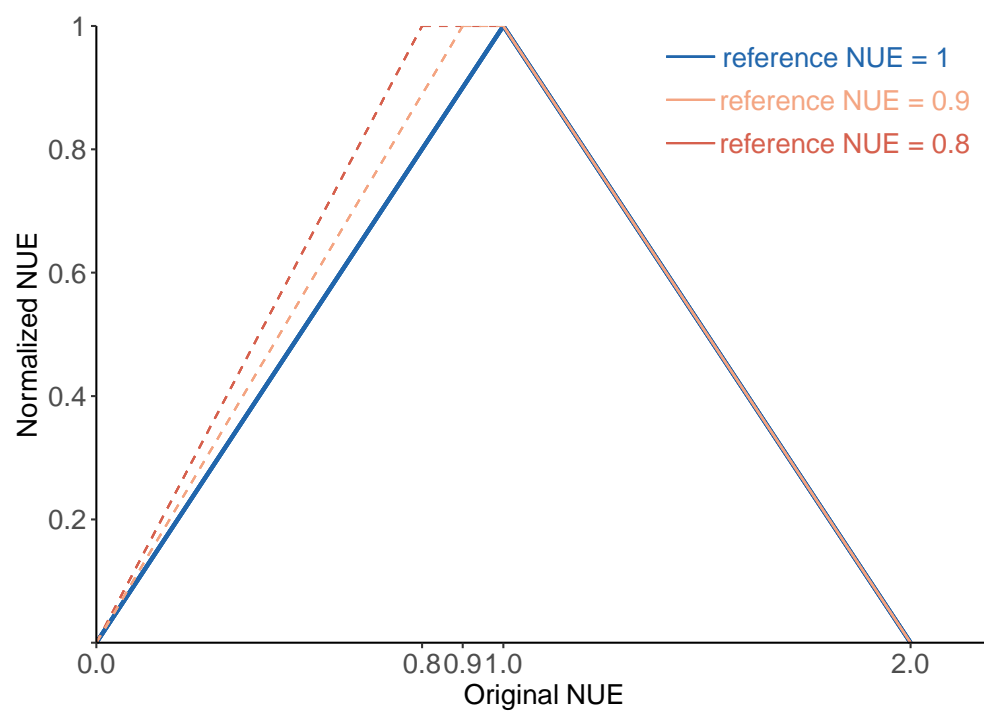


Fig. S1 Methods for normalizing NUE with different reference NUE values.

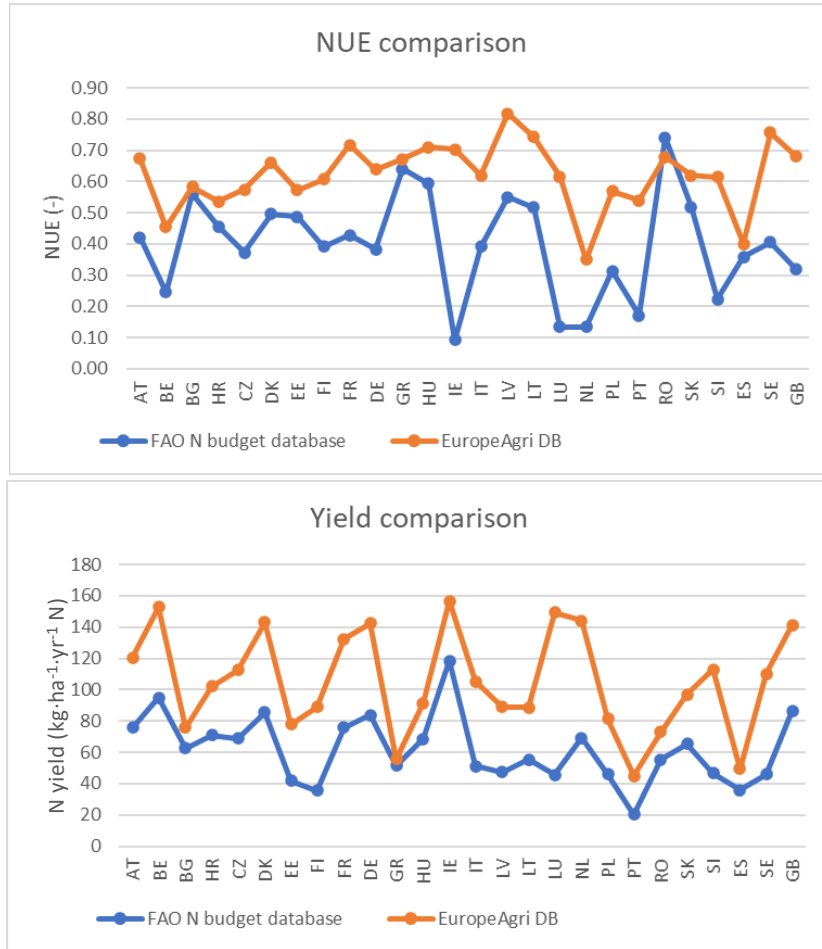


Fig. S2 Average cropland NUE (top) and cropland N yield (bottom) over the period 2014–2018 for 26 EU countries according to the FAO nutrient database (blue line) and the EuropeAgri DB (orange line)^[3].

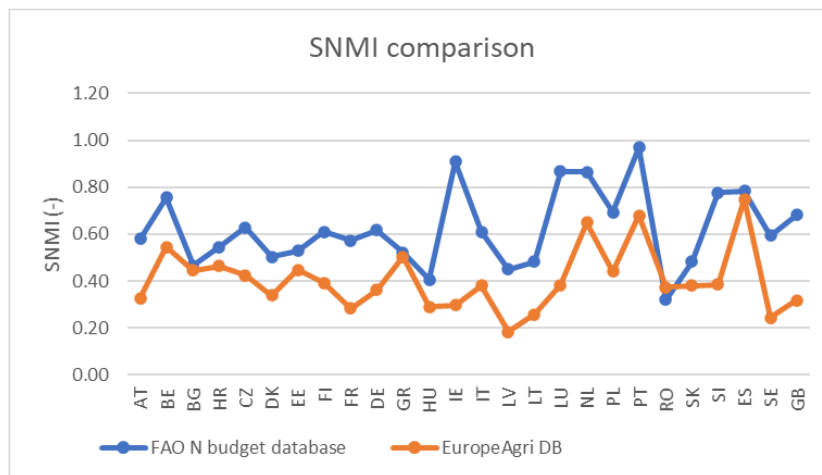


Fig. S3 SNMI scores for 26 EU countries calculated using data on NUE and N yield from the FAO nutrient budget database (blue line) and the EuropeAgri DB (orange line)^[3].

REFERENCE YIELD TEST

The reference yield is an important parameter in the calculation of SNMI (equation 2), measuring the progress of a country towards achieving a certain yield target. The reference yield was determined as a universal yield target (i.e., 90 kg ha⁻¹) for all countries in the global assessment presented in this study. In addition to using the universal target, the reference yield can also be determined with region-specific targets considering the limitation of regional ecological and socioeconomic conditions. Therefore, we designed two sensitivity tests to investigate how SNMI values change as the reference yield changes from a universal target to region-specific targets.

In the first test, we calculated SNMI for each country with country-specific reference yield derived from attainable yields ($Yield_{att_{cr}}$) for 155 countries and 16 crops (cr) from Mueller et al.^[4]. The yield level was converted to N yield level with crop-specific N content parameters (NC_{cr})^[5]. Considering potential discrepancies in the yield levels used by Mueller et al. in the baseline year ($Yield_{2000_{cr}}$) and FAOSTAT, we scaled the attainable yield to align with the FAOSTAT record, which we used for SNMI assessment in this study. Therefore, the definition of the country-specific reference yield is defined as below.

$$NYield_{ref} = NYield_{FAO,2000} \times \frac{\sum_{cr} Yield_{att_{cr}} \cdot NC_{cr}}{\sum_{cr} Yield_{2000_{cr}} \cdot NC_{cr}} \quad (S1)$$

This definition of reference yield can be applied to calculate the normalized yield ($NYield^*$) in equation 2 (main text) for each country. The equation of $NYield^*$ can be further simplified to the one below for estimating $NYield^*$ around year 2000.

$$NYield^* = \begin{cases} \frac{\sum_{cr} Yield_{2000_{cr}} \times NC_{cr}}{\sum_{cr} Yield_{att_{cr}} \times NC_{cr}} & (NYield \leq NYield_{ref}) \\ 1 & (NYield > NYield_{ref}) \end{cases} \quad (S2)$$

With the $NYield^*$ calculated with country-specific reference yield, we calculated SNMI for each country and compared it with the SNMI calculated with a universal reference yield (90 kg ha⁻¹ yr⁻¹ N).

In the second test, we calculated SNMI values at grid level (see Fig. 6 in main text) to highlight sub-national variation in SNMI. SNMI values were calculated using either the universal reference yield of 90 kg ha⁻¹ N (left panels in Fig. 6) or a region-specific reference yield based on the ratio current/attainable yield as described above (right panels in Fig. 6). Gridded data on crop N yield and NUE for the year 2010 at a spatial resolution of 0.5 × 0.5 degrees were obtained from the IMAGE model^[6]. Current and attainable yields from Mueller et al.^[4] at country-level were aggregated to the level of 26 world regions defined in IMAGE^[7].

DATA QUALITY

An accurate SNMI assessment relies on high-quality data on N budgets, however, estimates of different N budget terms can vary widely across global datasets^[2], urging for more collaborative efforts to improve N budget quantification globally. In this study, we used data on N yield and NUE from the FAO nutrient budget database^[2] as it provides consistent, long-term data on nutrient budgets for most global countries. However, derived scores need to be interpreted in the light of substantial uncertainties in the FAO nutrient budget data. For example, fertilizer and applied manure N in the FAO nutrient budgets may not exclude these inputs to non-cropland (based on FAOSTAT domains ‘fertilizer by nutrient’ and ‘livestock manure’), while N removal represents N removal by crops based on FAOSTAT crop statistics, which do not include grass production and most fodder crops. Even though the fraction of fertilizer applied to pastureland is very low globally, this fraction could be large in countries with large area of intensively managed grassland, and the information about such fraction is very limited. Consequently, the NUE from FAO nutrient budget database tends to be lower than other database for cropland NUE, especially in countries with a large area of grassland and fodder crops, such as the Netherlands and Ireland. In addition, the cropland area used to calculate per-hectare N yields (in kg ha⁻¹ yr⁻¹ N) from total crop N removal (in kt yr⁻¹ N) in the FAO database is based on data from the FAOSTAT land use domain, where ‘cropland’ includes fodder crops and temporary grassland that are not included in the yield data.

We compared data on N yield and NUE from FAO for 26 EU countries with data from EuropeAgriDB v1.0^[3], a recent dataset of crop production and N flows in European cropland and grassland for the period 1961–2019^[3].

The EuropeAgriDB partly relies on FAO data for the assessment of crop yields and areas but includes a more detailed assessment of (1) crop N removal for crops not considered by FAOSTAT, such as fodder crops and (2) the allocation of manure and fertilizer inputs to arable crops, fodder and grassland. Results show that NUE estimates for cropland (including major crops, fodder crops, and temporary grassland, but not permanent grassland) from EuropeAgriDB are higher than NUE estimates from FAO for all countries (except Romania, Fig. S2, top). This result is due to a higher N removal in the EuropeAgriDB (as N removal by fodder crops and temporary grassland is also considered), as well as a lower N input (as EuropeAgriDB excludes the share of total fertilizer and manure inputs applied on permanent grassland). Differences are substantial in some countries (e.g. for Ireland 0.09 vs. 0.70 for Ireland or 0.17 vs. 0.54 for Portugal). Similarly, estimated crop N removal per hectare from EuropeAgriDB is for all countries (Fig. S2, bottom). Based on the EuropeAgriDB, 16 out of 26 countries have achieved a yield higher than the reference of $90 \text{ kg ha}^{-1} \text{ yr}^{-1} \text{ N}$, while this is only two countries based on FAO data. Comparison of country-level SNMI scores calculated based on both datasets (Fig. S3) show consistently lower SNMI values (i.e., better performance) based on EuropeAgriDB data (both due to higher NUE and higher N yield). This comparison demonstrates the level of difference between N budget databases and provides insights for potential improvement in the global FAO database by leveraging new and detailed regional assessment such as EuropeAgriDB.

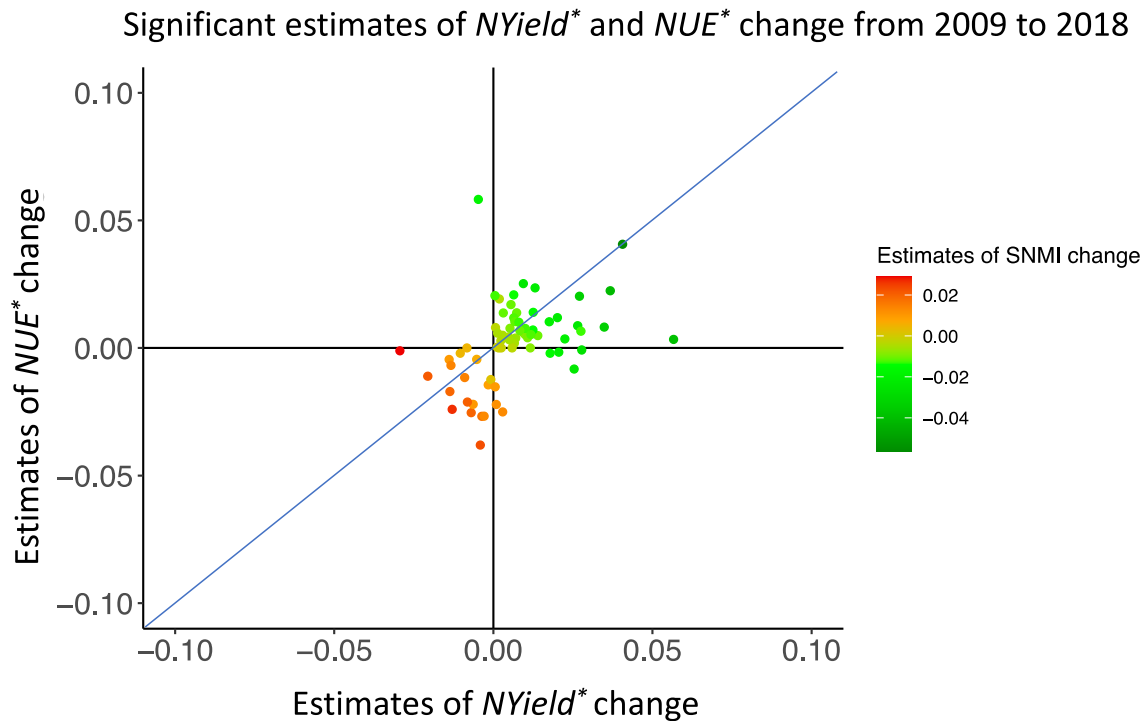


Fig. S4 Four quadrants with linear regression estimates of $N\text{Yield}^*$ and NUE^* change from 2009 to 2018. The color of the dots represents significant linear regression estimates of SNMI change ($P < 0.05$).

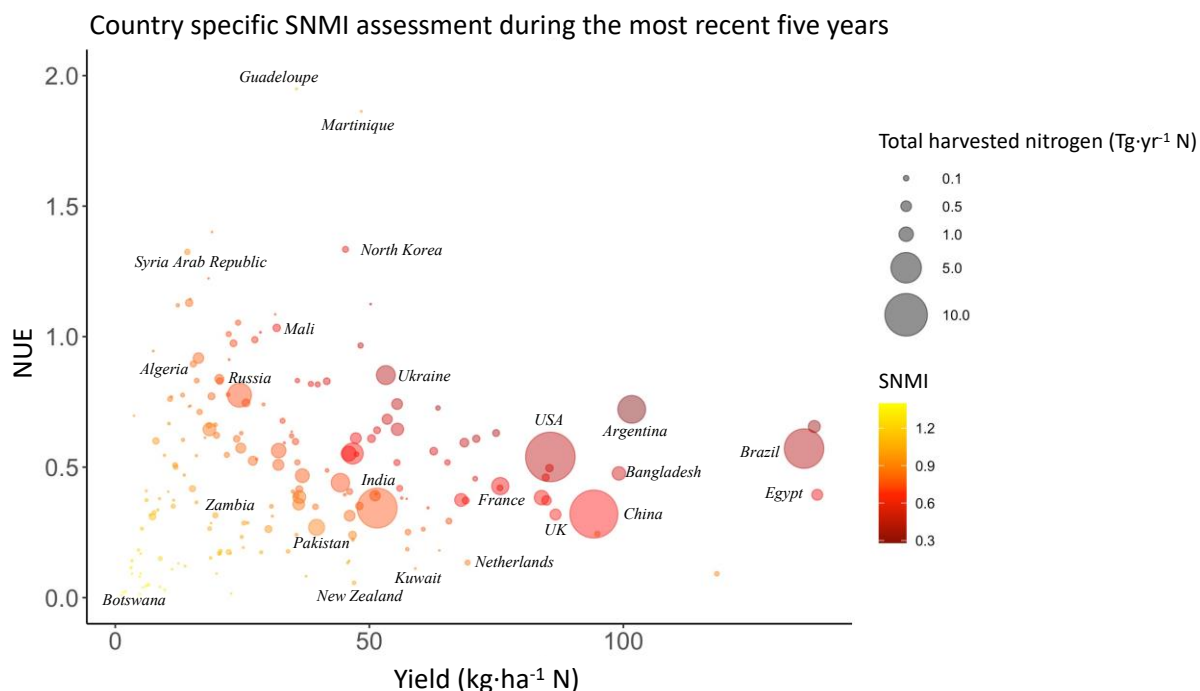


Fig. S5 An overview of the SNMI, Yield, NUE and N production of selected countries for the period 2014–2018. The x axis represents the yield ($\text{kg ha}^{-1} \text{N}$) each country and the y axis represents the NUE. The size of the bubble represents the total harvested N ($\text{Tg yr}^{-1} \text{N}$), and the color scale shows the five-year average SNMI score for each country.

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