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RESEARCH ARTICLE

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

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KEYWORDS

global assessment, indicator, nitrogen management, sustainable agriculture, sustainable development goals

HIGHLIGHTS

- A composite N management index is proposed to measure agriculture sustainability.
- Nitrogen management has been moving towards sustainability targets globally.
- The improvement was achieved mainly by yield increase, while nitrogen use efficiency (NUE) stagnated.
- No country achieved both yield and NUE targets and spatial variation is large.
- Region-specific yield targets can be used to supplement the standard sustainable nitrogen management index (SNMI).

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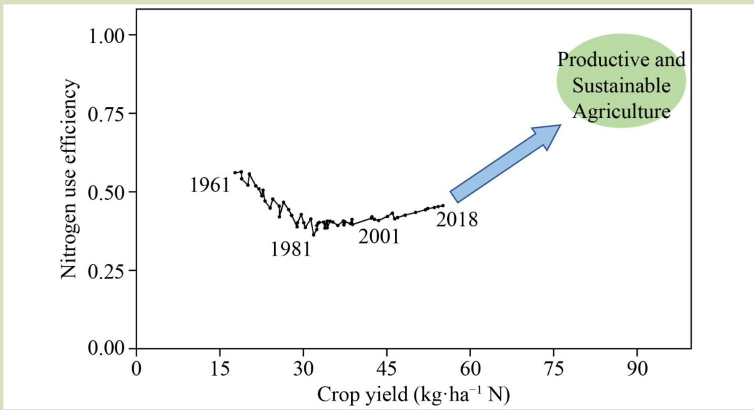
GRAPHICAL ABSTRACT



ABSTRACT

To represent the sustainability of nitrogen management in the Sustainable Development Goals indicator framework, this paper proposes a sustainable nitrogen management index (SNMI). This index combines the performance in N crop yield and N use efficiency (NUE), thereby accounting for the need for both food production and environmental protection. Applying SNMI to countries around the world, the results showed improvement in the overall sustainability of crop N management over the past four decades, but this improvement has been mainly achieved by crop yield increase, while global NUE has improved only slightly. SNMI values vary largely among countries, and this variation has increased since the 1970s, implying different levels of success, even failure, in improving N management for countries around the world. In the standard SNMI assessment, the reference NUE was defined as 1.0 (considered an ideal NUE) and the reference yield was defined as 90 $kg \cdot ha^{-1} \cdot yr^{-1}$ N (considering a globally averaged yield target for meeting food demand in 2050). A sensitivity test that replaced the reference NUE of 1.0 with more realistic NUE targets of 0.8 or 0.9 showed overall reduction in SNMI values (i.e., improved performance), but little change in the ranking among countries. In another test that replaced the universal reference yield with region-specific attainable yield, SNMI values declined (i.e., improved performance) for most countries in Africa and West Asia, whereas they increased for many countries in Europe and South America. The index can be improved by further investigation of approaches for setting region-specific yield targets and high-quality data on crop yield potentials. Overall, SNMI offers promise for a simple and transparent approach to assess progress of countries toward sustainable N management with a single indicator.

1 INTRODUCTION

Improved nitrogen management in agricultural production is fundamental for achieving the Sustainable Development Goals (SDGs). N is arguably the most critical nutrient for agricultural productivity, and consequently for food security and bioenergy supply (SDGs 2 and 7)[1]. Also, since N, unlike phosphorus, does not chemically sorb to soil minerals in large quantity, soil N buffering is relatively small and crop growth reacts quickly to a reduction in N input. However, the rapidly increasing reactive N load from human activities to the earth system has led to severe environmental issues[2] from water and air pollution on local and regional scales (SDGs 6 and 14) to ozone depletion and climate change on a global scale (SDG 13), threatening ecosystems and human health (SDGs 3 and 15). Currently, the amount of reactive N added by agricultural production to the earth system amounts to 140 $Tg \cdot yr^{-1}$ N, accounting for 90% of all reactive N added by human activities[3] and exceeding the estimated planetary boundary that delineates the safe operating space for humanity[4,5]. Efficiently managing N in agricultural production and thus enhancing the N use efficiency (NUE) is critical for bringing human disturbance of N cycles back to the safe operating space, balancing food security and environment targets, and achieving SDGs[6].

Despite the importance of N management for SDGs, none of the indicators in the global SDG indicator framework adopted by United Nations General Assembly evaluates N management or N pollution directly[6]. Only one indicator has been proposed for measuring progress toward sustainable agriculture, namely the proportion of agricultural area under productive and sustainable agriculture, which is assessed based on farm surveys and 11 sub-indicators[7]. Among these sub-indicators, only management of fertilizers is directly related to agricultural N management. However, scoring for this indicator is based on the number of management measures taken to reduce pollution risk, rather than the actual performance of the N management considering the need for both reaching target crop yields and limiting N pollution by losses to air and water[8]. In addition to the UN, a growing number of countries and organizations are developing indicator lists to assess progress of countries toward SDGs or impacts on the environment[9–12], but few included indicators that measure the performance of agricultural N management[13,14].

While several N indicators are used for guiding on-farm N management and regional environmental and agricultural policies, directly applying these indicators within the more complex SDG indicator framework is problematic. For example, NUE, defined as the fraction of all N inputs (fertilizers, manures, biological N fixation, atmospheric N deposition) that is harvested as crop products[15], has been widely used to indicate the efficiency of N use in agricultural production. NUE is usually considered to be positively related to the environmental performance of agricultural production, and a good candidate to evaluate performance of countries under SDG2, especially for sustainable agriculture. However, while an increase of NUE from 0% to 100% indicates improvement in efficiency of N use, a continued increase beyond 100% implies soil mining (i.e., more N is being removed from the soil at harvest than is being returned), which degrades soil fertility and lowers crop yield in the long-term. In addition, historical NUE trajectories at the country level suggest that NUE is usually very high when both N inputs and crop yields are low[15], which is not compatible with achieving the first part of SDG2 of reducing hunger. Therefore, NUE needs to be put in context of crop yield. The N management challenge is to produce enough food with low N losses, implying high crop yields at high NUE[6].

To represent the sustainability of N management within the SDG indicator framework, including the need for both food production and environmental protection, we proposed a sustainable nitrogen management index (SNMI). We first report its principle and the way in which we parameterize the index for global scale application (Section 2), followed by an evaluation of trends and spatial variation in the SNMI for countries around the world (Section 3). Finally, we discuss its advantage and limitations, and indicate directions for future improvement (Section 4).

2 THE SUSTAINABLE NITROGEN MANAGEMENT INDEX: PRINCIPLE AND PARAMETERIZATION

2.1 The proposed indicator

To provide a more comprehensive measurement of the sustainability of the agricultural production in a single index, we propose an agricultural SNMI, which considers two important efficiency terms in crop production, namely NUE and land use efficiency (crop yield, *Yield*), in a one-dimensional ranking score (Fig. 1).

More specifically, SNMI calculates geometrically how far the current position of a country in the normalized NUE (*NUE**) and normalized yield (*NYield**) space is from a reference point in a two-dimensional graphic (Fig. 1). Here *NUE** is defined as NUE divided by a reference NUE ($NUE_{ref} = 1$) and NUE values > 1 are adjusted downward to avoid inflating the score due to mining of soil N. *NUE** is set to zero in few instances where N inputs in a country are so low that NUE > 2 (See Fig. S1 for further explanation). The normalized crop yield is defined as the crop yield divided by a reference crop yield ($NYield_{ref}$ = 90 kg·ha^{-1}). The reference yield level is defined to measure progress of a country toward achieving a certain yield target, which addresses land use efficiency and food security. Sustainable N management will be reflected by SNMI values close to zero, as both yield and NUE approach their targets. Both normalized NUE and yield values are kept within the same range (0–1) so that the composite SNMI value is less likely to be biased toward yield or NUE performance due to different value ranges. As more data become available, the SNMI could be reviewed and improved by including more efficiency terms in crop production, such as water use efficiency, in a multidimensional space[16].

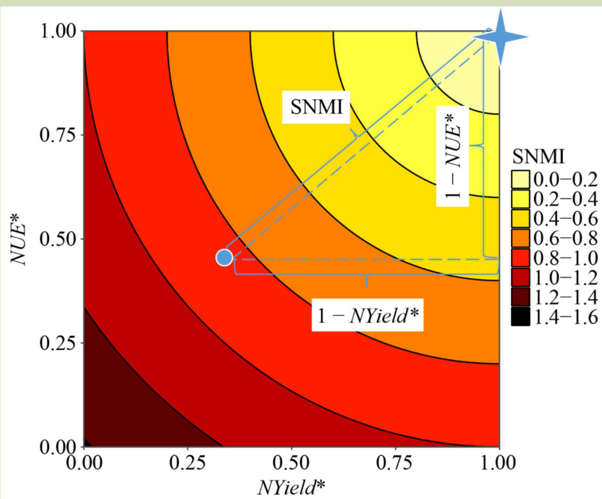


Fig. 1 Graphical representation of the calculation of the sustainable nitrogen management index (SNMI) based on normalized N yield (*NYield**, defined in Eq. (2)) and N use efficiency (*NUE**, defined in Eq. (3)). The blue star corresponds to the reference points (target values) for NUE and yield; while the blue circle is an example of a country that has a normalized NUE and N yield level at *NUE** and *NYield**, respectively. The low values in the upper right are the desired scores (highest ranking).

The mathematical definition of SNMI is the Euclidean distance from an ideal point targeted for NUE and yield, the equation is as follows (see Fig. 1 for an example):

$$SNMI = \sqrt{(1 - NYield^*)^2 + (1 - NUE^*)^2} \tag{1}$$

where,

$$NYield^* = \begin{cases} NYield/NYield_{ref} & (NYield \leqslant NYield_{ref}) \\ 1 & (NYield > NYield_{ref}) \end{cases} \tag{2}$$

$$NUE^* = \begin{cases} NUE/NUE_{ref} & (NUE \leqslant NUE_{ref}) \\ 1 & (NUE_{ref} < NUE \leqslant 1) \\ 1-(NUE-1) & (1 < NUE \leqslant 2) \\ 0 & (NUE > 2) \end{cases} \tag{3}$$

2.2 Parameterization for global assessment

Based on this proposed method, we computed the SNMI using country-level data on N yield and NUE from the FAO soil nutrient budget database[17,18]. This database is used in this study because it provides consistent data on N budgets with large spatial (205 countries or regions) and temporal (1961–2018) coverage. Further improvement of this database is needed, including an improved allocation of N fertilizer and N manure inputs to croplands and an improved assessment of the cropland area[17] (Fig. S2 and Fig. S3, see the section on data quality in supplementary materials). However, resolving issues around data quality is beyond the scope of this paper, which focuses on establishing the methodology for the indicator that could be applied using data from different databases on various spatial scales.

To illustrate the principle and evaluate both global scale trends and the country variation in current SNMI values, we used a reference yield level of 90 $kg \cdot ha^{-1} \cdot yr^{-1}$ N, which is approximately the required N yield, averaged globally, to meet 2050 crop production targets without cropland expansion[19]. For applications of SNMI on country and subnational scales, the reference NUE can be adapted according to a maximum feasible NUE under best management at which no soil mining occurs (see Section 4.2) and the reference yield can be adapted according to a yield target for a country or a region (see Section 4.3). Regardless of the reference yield chosen, SNMI credits countries with both high yield and high NUE with the desired ranking scores, and this approach is consistent with an evaluation in 2015[15].

3 RESULTS

3.1 Trends in global scale SNMI

The global average SNMI value declined from 0.91 in 1961 to 0.68 in 2018, implying that N management has been moving toward sustainability targets in terms of increasing crop yield and/or NUE (Fig. 2(a)). However, this improvement in SNMI has been mainly achieved by more than a doubling of crop N yield, while global NUE has improved only slightly from 0.39 to 0.45 in the past four decades (Fig. 2(a)).

From 1961 to 2018, SNMI values from all countries exhibited a clear left-shifted pattern as average SNMI values have decreased (1961–1970, 0.99 and 2011–2018, 0.88; Fig. 2(b)). However, this overall improvement in N management was accompanied with larger standard deviations among countries (1961–1970, 0.19 and 2011–2018, 0.25), as illustrated by a wider range in the distributions (Fig. 2(b)). This inconsistency between the overall N management improvement globally and enlarged disparity among countries highlights the need to investigate the pattern of spatial variation and its causes in current SNMI among countries.

3.2 Spatial variation in current SNMI and recent trends

The SNMI values for individual countries (average for 2014–2018) ranged from 0.28 to 1.40 (Table S1). No country has achieved both yield and NUE targets to attain an ideal SNMI score of 0. Eight countries, together accounting for 33% of global crop N production, have achieved the reference yield level ($NYield_{ref}$ = 90 $kg \cdot ha^{-1} \cdot yr^{-1}$ N), but their NUE level ranged from 0.01 to 7.95, indicating the need for significant improvement in some of these countries (Table S1). In contrast, very few countries have reached the reference NUE level (NUE_{ref} = 1) since crop production is a very leaky system the reactive N inputs are often converted to N_2 or lost to air or water as other forms of reactive N during N cycling processes.

During this period, China and India had the highest (worst) SNMI scores among the top five crop producing countries, highlighting the need for improving N management in these countries (Fig. 3(a)). The relatively high (poor) SNMI score of China is mainly due to the low NUE (0.32) while poor score for India resulted from both low NUE (0.34) and low $NYield^*$ (0.57, Fig. 3(b)). In absolute terms, the average N yield in India is 52 $kg \cdot ha^{-1}$ N and in China 94 $kg \cdot ha^{-1}$ N (Table S1), leading

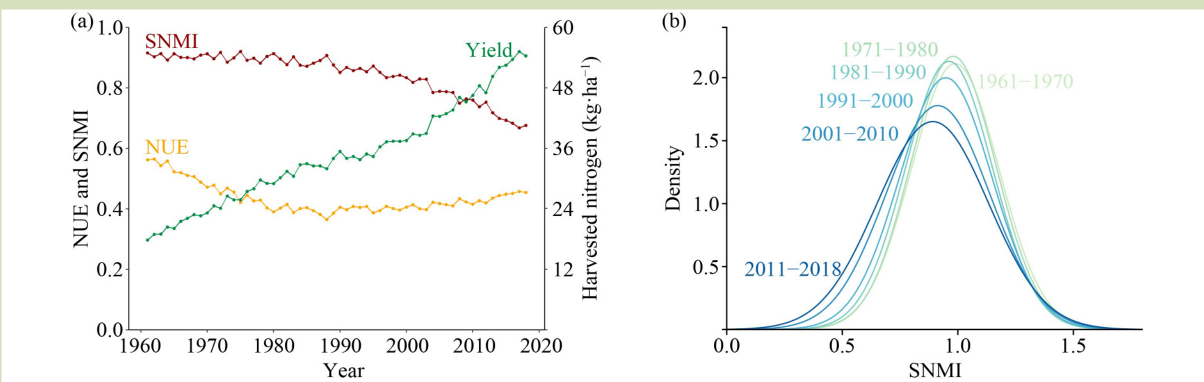


Fig. 2 (a) Historical records of global N use efficiency (NUE), yield ($kg \cdot ha^{-1}$ N), and sustainable nitrogen management index (SNMI); (b) distribution shifts of country-level SNMI for countries around the world from 1961 to 2018 using ten-year average. Each colored curve is the normal density curve of country-level SNMI values for a year. Recall that SNMI values approaching zero indicate progress on improved sustainable use of N.

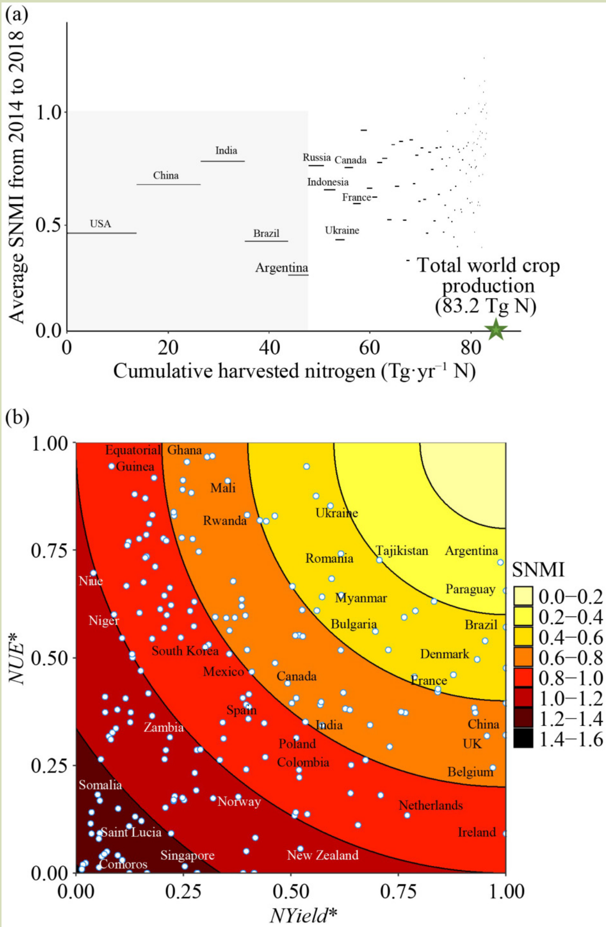


Fig. 3 An overview of the sustainable nitrogen management index (SNMI) for countries around the world in the context of N production level (a), and normalized N use efficiency (*NUE**) and N yield (*NYield**) values (b) for the period 2014–2018. More specifically, (a) shows the relative importance of each country in the global crop production and its level of sustainability in N management. The width on the *x*-axis represents the cumulative harvested nitrogen ($Tg \cdot yr^{-1}$ N) for all countries arranged in a descending order, and the height on the *y*-axis is determined by the five-year average of SNMI for each country, showing its level of sustainability in N management. The light gray shades area covers countries with top five harvested nitrogen amount. In (b), the *x*-axis represents the normalized yield for each country and the *y*-axis represents the normalized NUE. The non-normalized data are presented in Fig. S5.

in the latter case to an *NYield** of 1. To improve SNMI in these countries, China will need to focus on improving NUE, while India will need to almost double the crop yield with more efficiently managed N inputs. To achieve these improvements, it is not only important to develop and promote more efficient N management technologies and practices[20–22], but it is also necessary to improve the socioeconomic conditions to enable more efficient N use during crop production (e.g., gradually phasing out the N fertilizer subsidies and incentivize the adoption of best management practices)[15,23]. Average country-level SNMI scores and ranking for the period 2014–2018 are given in Table S1.

Between 2009 and 2018, 53 of 199 countries had significantly decreasing trends in SNMI (i.e., improvement in N management sustainability), and 21 had increasing trends in SNMI (i.e., deterioration in N management sustainability). These changes in SNMI were due to either changing NUE or changing N yield or both (Fig. S4). In the 125 countries where SNMI did not change between 2009 and 2018, it is possible that NUE and N yield changed, but the effect of an increase in N yield on the SNMI score was canceled out by a simultaneous decrease in NUE (or the reverse).

4 DISCUSSION

The SNMI indicator provides a useful metric for each country to track its trajectory of progress toward the dual goals of increasing agricultural land use efficiency and nitrogen use efficiency, and thus has great potential to represent sustainability of N management and its role in the sustainability of agricultural production in SDGs assessments. Country-scores for SNMI in the current SDG Report[9] are based on a universal reference yield of 90 $kg \cdot ha^{-1} \cdot yr^{-1}$ N (equal to the average global required nitrogen yield to meet demands in 2050 without land expansion), and a universal reference NUE of 1.0, while scores for regions with NUEs > 1 are adjusted considering potential soil mining. However, caveats need to be taken into consideration when applying and interpreting SNMI, considering its composite character and the potential impacts of different achievable crop yield and NUE among regions.

4.1 Limitations of a composite indicator

Overall, the advantage of the SNMI is that it captures progress toward both increasing the benefits of N for crop production and reducing the costs of environmental N losses. However, since the SNMI is a composite indicator, some countries may receive the same score for very different reasons. For example, a country with a relatively high, normalized yield of 0.8 but a normalized NUE of only 0.2 would have the same score as a country with a normalized yield of only 0.2 and a normalized NUE of 0.8. The former would be producing more food (high land use efficiency) but would have a low SNMI score because of high pollution (low NUE), whereas the latter would have low pollution (high NUE) but have a low SNMI score because it is not meeting food production targets (low land use efficiency). Therefore, understanding comparisons of SNMI scores across countries may require disaggregating the one-dimensional SNMI score into a separate yield score and NUE score. Nevertheless, using the SNMI to assess national progress toward sustainable N management as one indicator for progress toward SDGs is useful in addition to possible disaggregated parameters.

4.2 Choice of the reference NUE

In the standard calculation, the reference NUE is set to 1.0, given that with NUE > 1, soil mining occurs, thereby degrading soil fertility and lowering crop yield in the long-term. However, mining of soil N likely already occurs at lower NUE values, due to losses of N gases (NH_3, NO_x, N_2O and N_2) to air and dissolved N (NO_3, NH_4 and DON) to water that occur even under natural circumstances. Currently, the maximum NUE under the most favorable circumstances is estimated at 0.9 (90%) since about 10% of the N input is generally lost even with excellent management regimes[24]. This effective maximum non-mining NUE may vary spatially due to different climate and soil conditions. An assessment of the spatial variation in the maximum feasible NUEs could be derived based on data from crop fertilization trials that measure N input and crop N uptake for different crops, environmental conditions and management regimes. While quantifying the maximum feasible NUEs is beyond the scope of this paper, a sensitivity test was performed to show how the SNMI value is affected by the choice of different reference NUE values. SNMI was calculated with the NUE* normalized with reference NUE values different from 1 (i.e., 0.8 and 0.9; see an illustration of the normalization methods in Fig. S1) and compared the results with the SNMI calculated based on the standard approach. When a lower reference NUE is applied, the *NUE** values increase and the SNMI values decline (Fig. 4). However, SNMI scores calculated with different reference NUE are strongly correlated, because most countries still have NUEs much lower than the reference NUE (i.e., 0.8–1.0), and consequently the choice of reference NUE has little impact on the SNMI ranking for most countries. As countries manage to improve NUE and move closer to 0.8, the choice of reference NUE will become more important for the SNMI assessment.

4.3 Choice of reference yield

As noted in the methods section, the reference yield for the global assessment is determined based on the global demand for crop production in 2050, with an underlying assumption that all existing croplands share similar responsibility to produce protein and to prevent further expansion of croplands into natural habitat. Such a common global target for N yield provides a consistent reference point across countries, but it does not consider the very different yield potentials among countries and regions due to different climate and soil conditions as well as different crop mixes.

Therefore, in addition to reporting an SNMI based on a universal yield target, we recommend accompanying it with an SNMI based on a country- or region-specific yield target. The yield target (i.e., reference yield) in a country or region could be determined by the yield potential, defined as the maximum

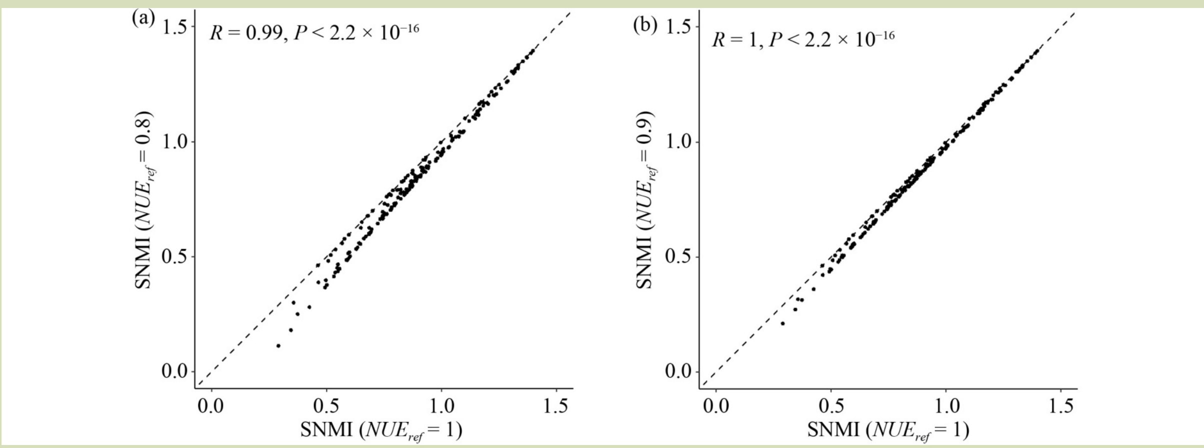


Fig. 4 Comparison of country-level sustainable nitrogen management index (SNMI) scores for the most recent decade using different reference N use efficiency (NUE) values for normalizing NUE. (a) $R = 0.99$, $P < 0.001$; (b) $R > 0.99$, $P < 0.001$. The dotted line is the 1:1 line.

possible yield for a given climate and soil under optimal management[25], a maximum attainable yield considering ecological and socioeconomic conditions (e.g., top 5% yield)[26,27], or a national yield target based on food demand and self-sufficiency[28]. To gain insight in the potential effect of using different reference yields, we calculated SNMI values with yield targets based on estimated attainable yields for arable land, defined as the 95th percentile yield that is achieved in a certain climate[25,29]. The test used estimates of current yields and attainable yields for 155 countries and 16 crops from Mueller et al.[26] and the yields were converted to N yields with crop-specific N content parameters[30] (see the section on reference yield test in supplementary materials).

We performed sensitivity tests to compare SNMI values using a universal reference yield (90 kg·ha^{-1}) with SNMI values using country-specific yield targets. While the SNMI values using country-specific yield targets are significantly correlated with the SNMI values using a universal yield target, many points fall below the 1:1 line, indicating that using country-specific yield targets decreases the reference yield for these countries (especially countries in Africa and West Asia), and consequently lowers their SNMI values (Fig. 5). Meanwhile, where the yield potential-based yield target is higher than 90 kg·ha^{-1}·yr^{-1} N, such as in Argentina and Brazil (partly due to a high proportion of N-rich crops such as soybean in the crop mix), the SNMI score increases after adopting the country-specific yield targets (i.e., data points above the 1:1 line). Hence, the use of country-specific yield targets results in some of the high and low SNMI values to move toward more moderate values. A similar picture (overall lower SNMI values, but with regional differences) emerges when calculating SNMI values at the grid-level using either a universal or region-specific yield targets (Fig. 6; see the section on reference yield test in supplementary materials).

The use of country-specific yield targets for the calculation of SNMI scores is hampered by the limited reliability of the attainable yield estimates as surrogates for the yield potential, as discussed in recent studies[27,34]. Projects such as the Global Yield Gap Atlas (GYGA), which provides high-quality data on actual yields and yield potentials (both under water-limited and irrigated conditions) for a variety of staple crops and countries[35]. GYGA yield potentials are estimated by a bottom-up approach using crop growth models calibrated for specific weather stations, and upscaled to the country-level using zones of similar climate[36,37]. Unfortunately, yield potential estimates based on such high-quality, bottom-up estimates are currently only available for selected countries and crops, and consensus has not been reached regarding how best to determine the yield potential for a region considering various crop and irrigation options. Although changing the

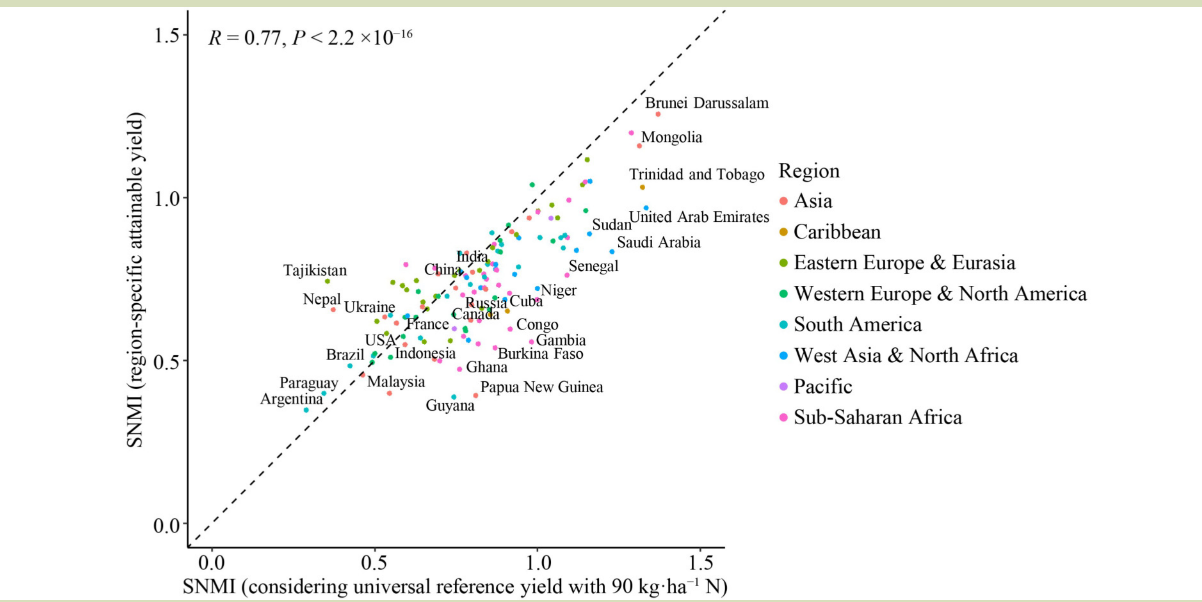


Fig. 5 Comparison of country-level sustainable nitrogen management index (SNMI) scores for the most recent decade using different reference values for normalizing yield. SNMI scores calculated with a universal reference yield (90 kg·ha^{-1}·yr^{-1} N) are shown on the *x*-axis, and SNMI scores calculated with country-specific yield targets are shown on the *y*-axis (R = 0.77, P < 0.001). The classification of countries into regions was based on Wendling et al.[31].

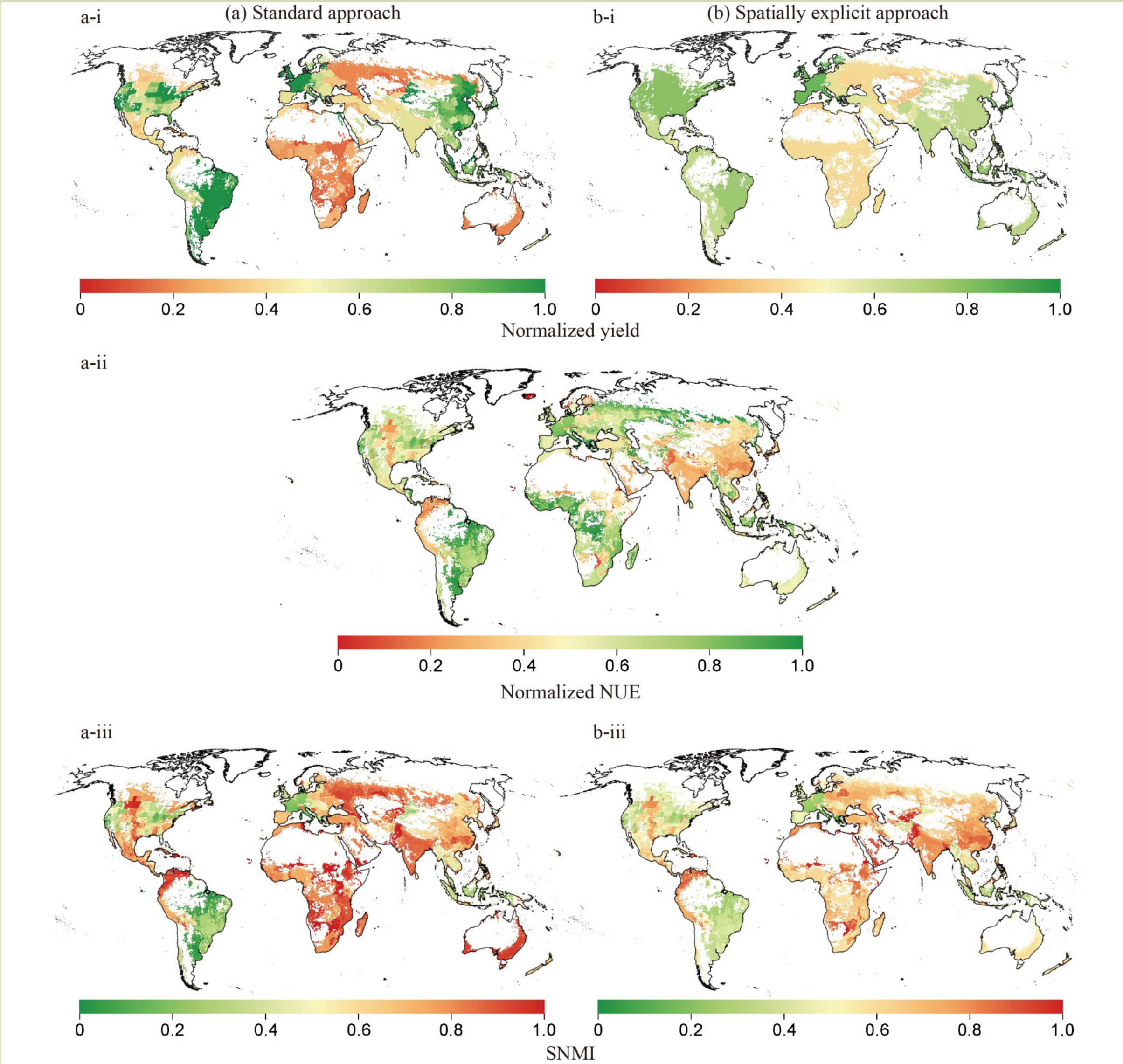


Fig. 6 Comparison of normalized yield (top), normalized NUE (middle), and SNMI (bottom) using different reference values for yield. (a) Using 90 kg·ha^{-1}·yr^{-1} N as the reference yield. (b) Using gridded attainable yields as the reference yield. Calculations are performed using gridded data on crop N yield and NUE from the IMAGE model for 2010[32,33] (spatial resolution is 0.5×0.5 degrees).

universal yield target to country- or region-specific targets may change ranking across countries, it will have little impact on the temporal trends of SNMI for each country.

5 CONCLUSIONS

The Sustainable Nitrogen Management Index provides a simple, transparent, and robust indicator of spatial and temporal patterns in agricultural sustainability, considering both cropland productivity and environmental impacts. Hence, it could be a useful addition to the SDG indicator framework. A global assessment of SNMI demonstrated that the sustainability of crop N management has improved globally over the past four decades, but the improvement has been mainly achieved by crop yield increase, with little improvement in NUE. The variation in SNMI values among countries is large and has increased over the past four decades. Further improvements of the index are possible. Rather than calculating SNMI using universal values for reference NUE and yield, for example, it would be possible to define region-specific reference values, considering the heterogeneous ecological and socioeconomic conditions for crop production. Our sensitivity test using more realistic NUE targets as reference value (i.e., 0.8

or 0.9 instead of the standard target of 1.0) showed a general reduction in SNMI values (i.e., improved performance), but had less impact on the spatial and temporal patterns. Another sensitivity test using country-specific reference yield values changed the SNMI values, as well as rankings, for some countries (e.g., reduced SNMI values for most countries in West Asia and Africa). Therefore, as more high-quality, regionally specific data on yield potentials become available, the SNMI index can become more regionally relevant. Future development of SNMI could also include applying it on field and regional scales and involving more efficiency terms in crop production.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2022458 contains supplementary materials (Table S1; Figs. S1–S5). Most data presented in this study are contained within the supplementary materials. Raw data supporting the findings are available from the corresponding authors upon reasonable request. Source data are provided with this paper. The code used to perform analyses in this study is generated in R 4.1.2 and is available upon request.

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Compliance with ethics guidelines

Xin Zhang, Yanyu Wang, Lena Schulte-Uebbing, Wim de Vries, Tan Zou, and Eric A. Davidson declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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