Benchmarking crop nitrogen requirements, nitrogen-use efficiencies and associated greenhouse gas mitigation potential

Methodology exploration for cereal production in sub-Saharan Africa

Working Paper No. 333

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

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RESEARCH PROGRAM ON
Climate Change, Agriculture and Food Security

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To cite this working paper

Hijbeek R, van Loon MP, van Ittersum MK, ten Berge HFM. 2020. Benchmarking crop nitrogen requirements, nitrogen-use efficiencies and associated greenhouse gas mitigation potential. CCAFS Working Paper no. 333. Wageningen, the Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

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Abstract

This working paper explores a generic method that can be used to benchmark nitrogen (N) input requirements for crop production and the efficiency by which inputs are used. Two types of N benchmarks are introduced: one for short-term and another for long-term assessments. We explain the underlying assumptions, data requirements and types of applications. Both benchmarking methods are especially suitable for regional, national or global analyses.

The proposed methodology is illustrated for cereal production (maize, wheat, rice, millet and sorghum) in ten countries in sub-Saharan Africa, under current and optimal nutrient management, for today and towards 2050. We show that agronomic nitrogen-use efficiency (NUE) can be two to four times larger than currently observed in on-farm trials for the long-term benchmark. Potential improvements in N input requirements are related to greenhouse gas (GHG) emission mitigation potentials, using scenarios that include population increase and dietary change, potential yield increase and avoided land reclamation. Here, we show that when following the current trajectory of yield trends while maintaining the low current nitrogen-use efficiency, GHG emissions from cereal production will be three times larger than sustainable intensification of cereals in sub-Saharan Africa.

The proposed N benchmarking method is most useful for regional or larger scale analyses and less useful for field assessments. Nonetheless, this might fill a gap in higher scale analyses, especially for estimating potential improvements in NUE and reducing GHG emissions. This working paper presents work in progress. In the future, we will test the proposed methodology on different case studies to evaluate its potential and finetune its operation.

Keywords

Crop production; nitrogen; efficiency; benchmarking; methodology; greenhouse gas emissions.

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Acknowledgements

This working paper was written as part of the *Bringing Climate-Smart Agriculture practices to scale: assessing their contributions to narrow nutrient and yield gaps* project, which belongs to the Low Emission Development Flagship from the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). The authors would like to thank Lini Wollenberg and Tek Bahadur Sapkota for reading a draft version of this manuscript and Noud van Dam and Hilde Vaessen for their support with data collection and analysis in earlier phases of this research.

Contents

Acronyms

GHG	Greenhouse gas
ha	Hectare
kg	Kilogram
N	Nitrogen
N-AE	Agronomic N-use efficiency
NFRV	N fertilizer replacement value
NUE	Nitrogen-use efficiency
P	Phosphorus
K	Potassium
Ya	Current crop yield data
YN	Yield obtained with N fertilizer application
Y^T	Target yield
Y0	Yield obtained without N fertilizer application
Yw	Water-limited potential

Introduction

Benchmarks are needed to gain insight into the sustainability of farming systems. Benchmarks can be used to compare environmental or socio-economic performance between different agricultural production systems or compare a particular production system to its potential. Agricultural benchmarks can be related to a number of dimensions such as yield (i.e., potential yield), land requirement, water productivity or biodiversity conservation. As such, benchmarks can give guidance on priority areas or types of actions needed. Since nutrient cycling is at the core of several agri-environmental issues (e.g., greenhouse gas (GHG) emissions, soil fertility, nitrate leaching), a benchmark on nitrogen (N) use or N-use efficiency (NUE) is particularly useful. Practices meeting the benchmark minimize nitrous oxide emissions. Such a benchmark can be used as a practical indicator for meeting best practice, certification, sustainable finance and meeting regulatory requirements.

Within the different directions suggested for sustainable farming systems (e.g., agro-ecological, intensive, organic, regenerative, circular or conservation agriculture), nutrient (e.g., N, phosphorus (P), and potassium (K)) inputs often play a key role. Some approaches suggest using fewer nutrients as a way forward (i.e., agro-ecological and regenerative agriculture). However, others recommend using more nutrients per ha (e.g., intensive agriculture) or changing the source of nutrient inputs (from mineral to organic inputs – e.g., organic and conservation agriculture). The approach most likely to improve a farming system's sustainability will depend on its specific context, including its current state. While low-input systems could benefit from using more external nutrient inputs to prevent soil mining, others (i.e., high input systems) could benefit from using fewer external inputs and increasing on-farm nutrient cycling to prevent nitrate leaching and reduce GHG emissions. Depending on the geographical scale and time horizon, an N-use benchmark may provide guidance to move in the desired direction (either increasing or decreasing nutrient inputs) and the distance to a more desired situation.

There is a wide variety of nutrient use indicators (such as output/input ratios agronomic N-use efficiency), but there is currently a lack of benchmarks for these indicators. One notable exception is the conceptual framework for the NUE indicator of the European Union Nitrogen Expert Panel (Oenema et al. 2015). This framework relates N output to N input and compares their difference and ratio versus certain target ranges. Outside the target ranges, soil N mining, nutrient accumulation or environmental losses may occur. Despite this approach's appeal, this framework is conceptual regarding how specified values require local soil fertility adjustments, and soil N supply remains unknown. Simultaneously, within a region and a certain time frame, this framework allows for comparisons between farms.

In this working paper, we propose an N-benchmarking method focused on agronomic nitrogen-use efficiency (N-AE, defined as additional grain yield over an unfertilized control, divided by the total dose of N applied, kilogram (kg)/kg), and N input requirement (kg N/ha) for a given target yield. We propose two types of benchmarks for each indicator: 1) a short-term benchmark and 2) a long-term benchmark. We relate these benchmarks to current N inputs, observed N-AE achieved under current management and GHG mitigation potentials for five cereal types in sub-Saharan Africa. Moreover, we explore implications for the current situation and towards 2050, thereby testing the usefulness of our proposed methodology.

Two types of N benchmarking: short-term and long-term

The current relation between N input and crop yield must be assessed and then compared to a (theoretical) potential relation used as the benchmark to benchmark the N input requirement. In this case, we define the potential as the minimum N inputs needed to achieve the same crop yield while maintaining soil fertility. This potential can be expressed in the total N input requirement (kg N per ha) or in the N-AE (kg additional grain yield per kg N applied), either using a short-timeframe or a long-timeframe.

The theoretical potential depends on the time horizon taken. For shorter-term assessments, soil N supply is at a given value, and changes in the soil N pool are ignored. For longer-term assessments, soil fertility should be maintained by replenishing the soil N pool.

The N input requirement is based on the current soil fertility status for short-term assessments while assuming either current or best crop management. Best management is defined as a package of existing crop management practices (e.g., tillage, cultivars, water and nutrient management and crop protection), resulting in the highest feasible N-AE.

Table 1. Characteristics of the two proposed benchmarks regarding soil fertility and nutrient management, related to the current situation.

	Soil N supply	**Management type**
1. Current nutrient management	Current soil N supply	Current
2. Short-term benchmark	Current soil N supply	Best
3. Long term benchmark	Future equilibrium soil N supply	Best

For longer-term assessments, the ‘minimum N input requirement’ (ten Berge et al. 2019) seems to be a suitable benchmark. It is the minimum amount of N input needed to sustain a target crop yield over the longer term, as well as soil fertility, given best management practices (Table 1). The minimum N input requirement can be used to identify cases where soil N mining might occur or where N application is excessive in the light of environmental emissions.

How to calculate the short-term, current N input requirement

To calculate the current N input requirement, two factors are taken into account: a) the current N-AE by which applied N is converted into harvestable products (i.e., grain yield for cereals); and b) current grain N uptake from soil N supply.

Current Agronomic N-use efficiency

N-AE may vary widely across regions and countries for a particular crop, depending on soil type, climate, and crop management especially. For a certain region of interest, N-AE can be estimated by collecting data from multiple fertilizer field experiments (preferably on-farm) where yield obtained with a certain N fertilizer application (YN) is compared to yield obtained without N fertilizer application (Y0). To account for other yield-limiting factors, both plots (with and without N) should receive sufficient P and K. The N-AE is then calculated by dividing the additional grain yield by the applied N (Eq. 1).

$$\text{N-AE} = (YN - Y0) / N \qquad \text{(Eq. 1)}$$

Current soil N supply

Soil N supply varies widely across sites, depending on previous management of a field. Depending on the investigation's objective, current soil N supply can be estimated by assessing yield in control plots of fertilizer experiments, preferably with no N and only P and K application. However, yield in control plots might not be representative of a wider region.

Alternatively, based on country or agricultural statistical data, current crop yield data (Ya) can be combined with current N inputs and N-AE to estimate soil N supply following Eq. 2. If current N input is derived from multiple sources, the N added as organic amendments should be multiplied with the N fertilizer replacement value (NFRV). Soil N supply is then given in mineral fertilizer equivalents.

$$\text{Soil N supply} = (Ya / NAE) - (N\ applied \times NFRV) \qquad \text{(Eq. 2)}$$

Current N-input requirement

Given a certain N-AE and soil N supply (as calculated using equations 1 and 2), the current, short-term N input required to achieve a certain target yield (Y^T) can then be calculated using Eq. 3.

$$\textit{Short-term N requirement} = (Y^T / NAE) - \textit{soil N supply} \qquad (Eq.\ 3)$$

How to calculate the short-term N benchmark

The short-term N benchmark can also be calculated using Eq. 3. However, the N-AE is not based on current farm management but on the upper range of observed N-AE values in field trials, representing best nutrient management. Alternatively, the internal N-use efficiency (kg grain produced per kg N uptake; Table 2) can be multiplied by the best attainable uptake efficiency (i.e., apparent fertilizer N recovery fraction). Preferably, these should indicate the additional efficiency and uptake of fertilizer N, compared to a control plot. For cereals, Dobermann (2005) estimated a range in fertilizer N recovery between 0.5 and 0.8 for well-managed cereal cultivation sites.

Table 2. Internal N-use efficiency (kg grain yield per kg N uptake in aboveground biomass) for five cereals for different relative target yields (Y^T - percentage of its potential yield). The given values are averages based on a variety of literature.

Relative Y^T (%)	Maize	Millet	Rice	Sorghum	Wheat
40	52	32	52	42	45
60	52	32	52	42	45
70	49	28	43	37	41
80	46	25	36	32	37

Source: yieldgap.org

How to calculate the long-term N benchmark

The ‘minimum N input requirement,’ as introduced by ten Berge et al. (2019), presumes that annual N input should match the total crop N uptake in aboveground biomass for the chosen target yield to sustain a steady-state equilibrium in the long-term. This allows, if grain only is removed from the field, total N losses to be equal to the amount of N in residues retained on the field[1]. This is probably a very conservative (low) estimate of losses and, consequently, the minimum N requirement should be viewed as a bare minimum. In cases where crop residues are removed, this long-term minimum requirement will be insufficient to sustain the target yield. ten Berge et al. (2019) applied this method to maize, where 25% to 40% of the total aboveground N uptake was in crop residues. Well-managed long-term maize experiments show that such a percentage of N loss might be unavoidable, as lower values were not encountered in the literature.

Here, we assume that similar relations will hold for the other four cereals investigated (rice, wheat, sorghum and millet). With N inputs equaling N uptake, the N-AE is equal to the internal N-use efficiency. This means that each kg of N applied on average and is taken up only once in the long run. Thus, N losses are fully compensated for by the re-use of N retained and recycled through the system.

N content of cereals varies with yield level. Under a given attainable yield ceiling, crops accumulate N as actual yield is pushed towards its upper limit by N application. Based on the literature, we assume that accumulation (increasing N concentration in biomass) starts from around 60% of the potential yield upwards. This reduces internal N-use efficiency.

The internal N-use efficiency thus depends on the closeness of a target yield to the local yield potential. In Table 2, standardized values for internal NUEs are given for yield levels up to ~ 60% of the yield potential in a location and (accounting for a parabolic decrease of yield response to N uptake) also the values for 70% and 80% of potential yield. Eq. 4 can then be used to calculate the minimum N input requirement (kg N/ha) for a certain target yield (Y^T, t/ha).

$$\textit{Long-term N input requirement} = \textit{N aboveground biomass} = (1000 / \textit{internal NUE}) \times Y^T \quad \textit{(Eq. 4)}$$

[1] In a numerical sense, this does not imply that all N in residues is lost, nor that no other N losses occur.

The data needs mentioned in the sections above can be obtained from a wide variety of sources, depending on the study scope. A potential list of possible data sources is given in Table 3.

Table 3. Data needs and sources to calculate current N inputs and N-AE, the short-term benchmark and the long-term benchmark (3)

Data need	Possible sources
Potential or water-limited potential yield	Crop models, Global Yield Gap Atlas (GYGA)
Internal NUE	Scientific literature, GYGA
Agronomic N-AE	Regional fertilizer experiments with at least a NPK treatment and a PK treatment
Current soil N supply	A) Based on crop yield in regional field experiments in absence of N application. B) Based on national or other statistics, using current yield (GYGA, national or other agricultural statistical data); current N inputs (FAOstat); current N-AE

Benchmark case: cereal production in Sub Saharan Africa

Here, we present an application of the introduced benchmarking method for five cereals. We apply the methodology to assess current N-AE and N input requirements for ten countries in sub-Saharan Africa and relate these to the benchmarks, at present and towards 2050.

Benchmarking actual and potential agronomic N-use efficiency

Using short-term fertilizer experiment data across sub-Saharan Africa as documented by OFRA (OFRA 2017; van Dam 2020), current N-AE for the respective cereals were calculated (Fig. 1). Scientific literature was searched for estimates of internal N-use efficiencies (kg grain N per kg N uptake; Table 2). These were used to calculate the short- and long-term benchmark N-AE values (Table 4). For the short-term benchmark, we used the mean fertilizer recovery value of Dobermann (2005) for well-managed cereal cultivation (i.e., 0.65).

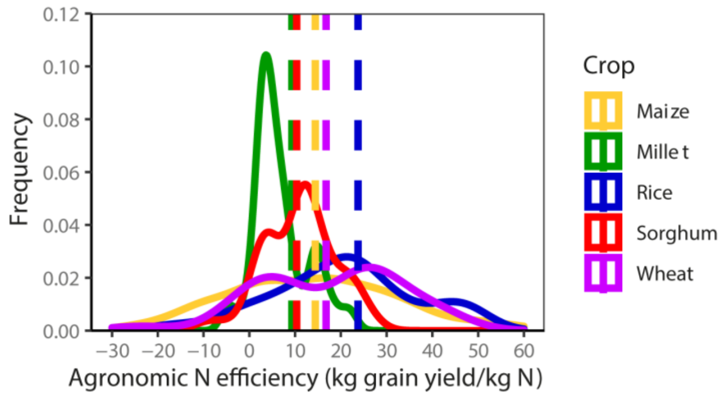

Figure 1. Current distribution of agronomic N-use efficiencies (N-AE) for maize, millet, rice, sorghum and wheat in sub-Saharan Africa (curves) with current mean values (dashed vertical lines).

The current N-AE for rice is similar to the short-term benchmark N-AE and is also closest to its potential (Table 4). For all cereals, the current N-AE is at least two times smaller than the long-term benchmark (i.e., 3.7, 3.6, 2.2, 4.2 and 2.8 times, respectively, for maize, millet, rice, sorghum and wheat). For all cereals, the current observed N-AE is closer to the short-term benchmark (i.e., 2.4, 2.3, 1.4, 2.7 and 1.8 times smaller, respectively), where ratios vary widely. The range in these figures suggests that, while for all five cereals large efficiency gains can be made, priority could be given to increase the efficiency of currently 'poor' performing crops or support production of currently 'good' performers.

Table 4. N-AE (kg grain yield/kg N applied) for five cereals. Current N-AE values are based on OFRA (2017), literature used to estimate the internal N-use efficiencies can be found at yieldgap.org, while the mean value of a fertilizer recovery under good management was obtained from Dobermann (2005).

	Maize	Millet	Rice	Sorghum	Wheat
Short-term current N-AE (SSA)	14	9	24	10	16
Short-term benchmark N-AE	34	21	33	27	29
Long-term benchmark N-AE	52	32	50	42	45

Benchmarking current N application rates

For current yields (Figure 2), we compared current N input rates with the long-term benchmark (Figure 3). Current N application rates were not specified per cereal type (FAO 2019); therefore, we used average values of fertilizer use per hectare of cropland.

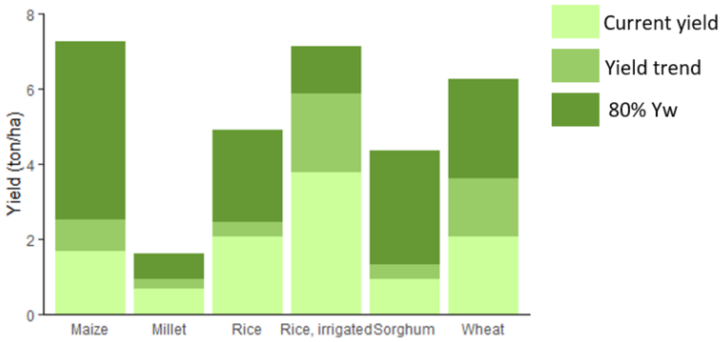

Figure 2. Average current cereal yield, yield when historical yield trends are extrapolated towards 2050 and 80% of water-limited potential yield (Yw) for the different cereals.

Depending on the country, current N inputs differ between almost zero and 40 kg N/ha. The long-term benchmark shows consistently higher N input requirements for all countries investigated, showing that the current N rates will likely lead to soil N mining and are not sustainable in the long-term.

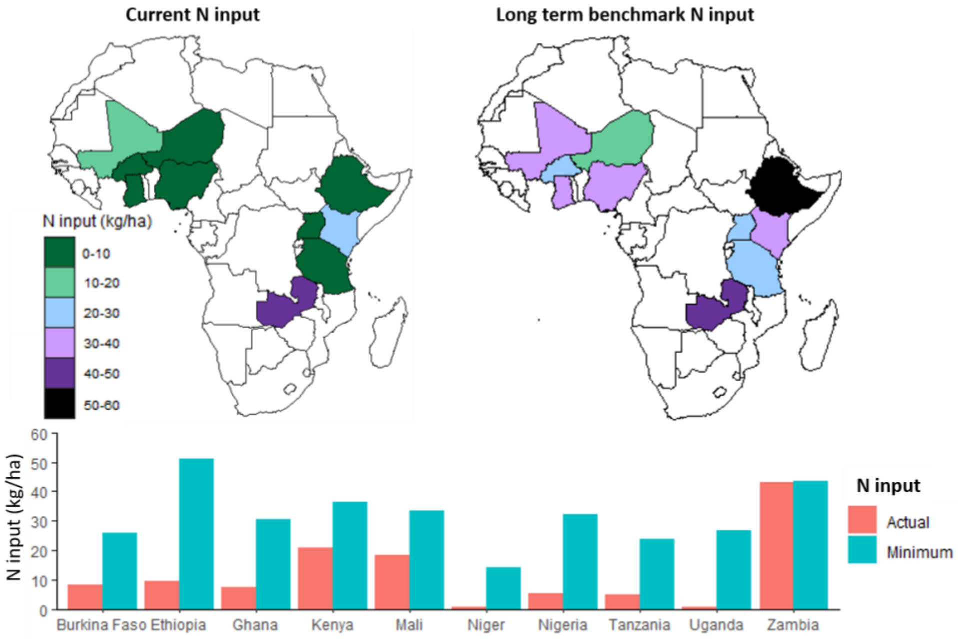

Figure 3. (a) Average current N input; (b) long term benchmark N input for current yield levels; (c) bar plot showing exact levels per country.

With a growing population and increases in food demands, yields will need to increase. Cereal demands are projected to increase nearly three times between 2015 and 2050 (van Ittersum et al. 2016, updated to 2015 as baseline). To achieve cereal self-sufficiency in 2050, cereal yield must approach 80% of its water-limited yield potential (Fig. 2). Figure 4 shows the N input requirement for current management, the short-term and long-term benchmark per cereal across the ten countries for current yields, yield trends and 80% Yw. The bars show that N inputs will need to increase substantially. Albeit with current nutrient management, N inputs will lead to much higher N input requirements than the short- and long-term benchmark, both based on more optimal management.

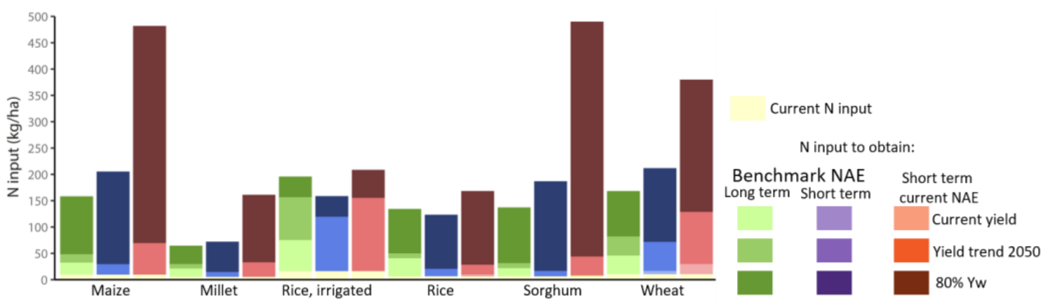

Figure 4. Benchmarking N input requirement towards 2050. N input requirements to obtain target yields (either current yield, 2050 yield based on yield trends or 80% Yw), based on the current NAE (red colors), short-term benchmark (purple colors) or long-term N-AE (green colors).

Benchmarking N input requirement and GHG emissions – towards 2050

N benchmarking can be used to estimate potential GHG emissions associated with different scenarios of achieving cereal self-sufficiency in 2050, either through intensification with higher crop yields or through crop area expansion (van Loon et al. 2019).

Using coefficients from the Intergovernmental Panel on Climate Change (IPCC) for GHG emissions associated with fertilizer production and application (direct and indirect emissions), Fig. 5a and Fig. 5b show the difference in GHG emissions for the current N-AE and the long-term benchmarks (orange and red) if current yield trends are extrapolated to 2050. With current yield trends, the current agricultural area will not meet projected cereal demand in 2050; the associated GHG emissions from land expansion are also shown (red, yellow and brown). With current yield trends, increasing N-use efficiency can contribute to some mitigation of GHG emissions (Fig. 5a to 5b; from 254 to 240 Mton CO_2 equivalent).

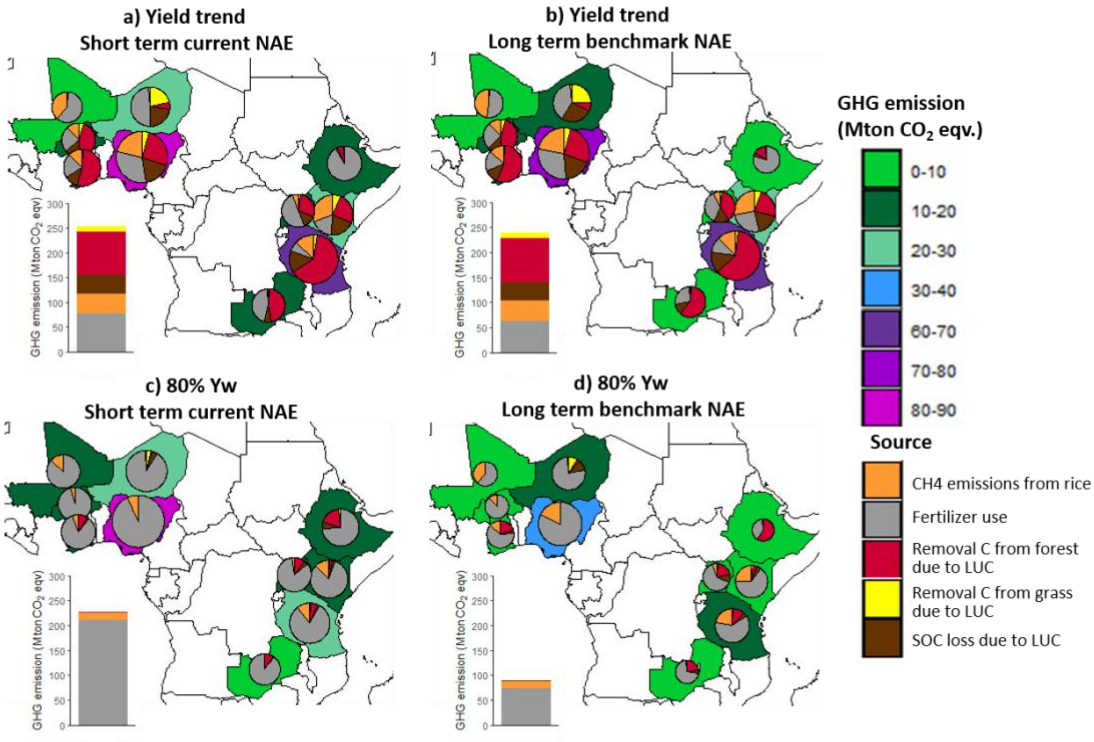

Figure 5. GHG emissions for five cereals and ten countries in sub-Saharan Africa in the year 2050 if a) historical yield trends are extrapolated (Yield trend) and current N management is used, or b) long term best N management is used (N benchmark), or c) cereal yields are 80% of water-limited potential (80% Yw), and current N management is

used, or d) long term best N management is used. Pie charts indicate the source of GHG emission (size of the circle also represents the amount of GHGs emitted).

Much larger GHG mitigation gains can be made if efficiency increases are accompanied by yield increases (Fig. 5c, d), preventing crop area expansion while reducing emissions from fertilizer production and use. Both Fig. 5c and Fig. 5d show GHG emissions associated when cereal yield reaches 80% Yw. Without improvements in N-AE, this leads to 227 Mton CO_2 equivalents. With improved N-AE, GHG emissions related to cereal production can remain limited to 90 Mton CO_2 equivalents.

Conclusion and recommendations

This working paper described a methodology to benchmark N input requirement and N-AE, illustrated by a study on five cereals in sub-Saharan Africa. For regional or continental analyses, the presented short- and long-term benchmarks can be used to detect possible soil N mining, over-fertilization or poor nutrient management. Moreover, it can also be used to support estimates of future crop nutrient input requirements. Our benchmarking method is less useful for individual farmers' fields, as the current soil N supply will be unknown. As shown, combined with technical coefficients on GHG emissions, this methodology can be used to calculate GHG emission mitigation potentials of increasing yield in combination with improving the N-AE of applied fertilizer. We are currently further underpinning and finetuning the approach with more empirical data.

We hope that this methodology might be used to inform government policies and private sector measures and decisions to move towards more sustainable farming systems in the longer term.

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