Efficiency of mineral and organic fertilizers across two continents

Working Paper No. 397

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

Renske Hijbeek
Marloes van Loon
Hein ten Berge
Gil Gram
Wytse Vonk
Luise Waldow
Martin van Ittersum

WAGENINGEN
UNIVERSITY & RESEARCH

CGIAR

RESEARCH PROGRAM ON
Climate Change,
Agriculture and
Food Security

CCAFS

Working Paper

Efficiency of mineral and organic fertilizers across two continents

Working Paper No. 397

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

Renske Hijbeek
Marloes van Loon
Hein ten Berge
Gil Gram
Wytse Vonk
Luise Waldow
Martin van Ittersum

To cite this working paper
Hijbeek R, van Loon MP, ten Berge HFM, Gram G, Vonk W, Waldow L, van Ittersum MK. 2021. Efficiency of mineral and organic fertilizers across two continents. CCAFS Working Paper no. 397. Wageningen, the Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

About CCAFS working papers
Titles in this series aim to disseminate interim climate change, agriculture and food security research and practices and stimulate feedback from the scientific community.

About CCAFS
The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) is led by the International Center for Tropical Agriculture (CIAT), part of the Alliance of Bioveristy International and CIAT, and carried out with support from the CGIAR Trust Fund and through bilateral funding agreements. For more information, please visit https://ccafs.cgiar.org/donors.

Contact us
CCAFS Program Management Unit, Wageningen University & Research, Lumen building, Droevendaalsesteeg 3a, 6708 PB Wageningen, the Netherlands. Email: ccafs@cgiar.org

Abstract

To mitigate climate change, greenhouse gas emissions from the agricultural sector need to decrease. In this light, increasing agronomic use efficiency of nitrogen (N) application (i.e., additional grain yield per kg of N applied) is a promising avenue to attain similar yields with less inputs in regions such as Europe (with high N inputs). In contrast, on the African continent, N inputs need to increase to raise yields, which may contribute to improved food security and prevent land use change. In such case, increasing agronomic N use efficiency (N-AE) and simultaneously increasing N inputs can also be a mitigation strategy by decreasing losses to the environment and improving profitability. In both contexts, it is relevant to understand how much N-AE can be increased in a certain location, compared to the current status, and which N source (organic and/or mineral fertilizer) will be most efficient.

In this working paper we present ongoing work on N benchmarking from the crop nutrient gap project (full name: Bringing Climate Smart Agriculture practices to scale: assessing their contributions to narrow nutrient and yield gaps). First, we compare current observed N-AE to the values they could potentially reach under optimal agronomic management. For this, we propose a new benchmarking method based on recent insights on the shape of N response curves and introduce the related 'degree of good agronomy'. Second, we compare the performance of mineral versus organic fertilizers for cereal cultivation on two continents (Europe and sub-Saharan Africa) based on large number of field experiments. Finally, we assess whether and how N-AE of mineral N fertilizer can be improved when combined with organic amendments.

Preliminary findings show that the proposed benchmarking method can work but relies on availability of data on soil N supply, potential yield and attainable yields. Currently, this information is sparsely available which might be a barrier for uptake of the method. We show that N supplied by mineral fertilizers is taken up more efficiently than from organic sources, with variation depending on the type of organic amendment. Variation was larger for sites in Africa than Europe, which makes targeted fertilizer strategies less straightforward. Based on European experimental data, we show that organic amendments do not increase the N-AE of mineral fertilizer N application, most likely due to the increased total N availability.

In future research, we hope to improve the data requirements for the proposed benchmarking method, assess drivers of variation for nitrogen fertilizer replacement values of organic amendments and disentangle effects of organic amendments on the efficiency of mineral fertilizer N use, while extending our analysis to tropical regions.

Keywords

Crop production; nitrogen; efficiency; benchmarking; mineral fertilizer; organic amendment

About the authors

Renske Hijbeek (coordinating author) is Assistant professor at the Plant Production Systems Group, Wageningen University & Research. Email: renske.hijbeek@wur.nl

Marloes van Loon is a Researcher at the Plant Production Systems Group, Wageningen University & Research

Hein ten Berge is a Senior Researcher at Wageningen Plant Research, Wageningen University & Research.

Gil Gram is a PhD researcher at the Department of Earth and Environmental Sciences, KU Leuven

Wytse Vonk is junior researcher at the Plant Production Systems Group, Wageningen University & Research

Luise Waldow is an MSc student at the Plant Production Systems Group, Wageningen University & Research

Martin van Ittersum is Professor at the Plant Production Systems Group, Wageningen University & Research.

Acknowledgements

This working paper was written as part of the project ‘Bringing Climate Smart Agriculture practices to scale: assessing their contributions to narrow nutrient and yield gaps’, which belongs to the Low Emission Development Flagship from the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). We thank Bastiaen Boekelo (WUR) for his great support with data analysis. This work was partly supported by a Senior Expert Programme (SEP) grant from the Dutch Scientific Council (NWO) for Martin van Ittersum (WUR).

Contents

Acronyms

FYM	Farmyard manure
GHG	Greenhouse gas
Ha	Hectare
ISFM	Integrated Soil Fertility Management
N	Nitrogen
N_{av}	Available nitrogen
P	Phosphorus
K	Potassium
Kg	Kilogram
N-AE	Agronomic N-use efficiency
Y_{max}	Attainable yield (not NPK limited)
Y_p	Potential yield
Y_r	Relative Yield
Y_w	Water-limited yield potential
N	Nitrogen
NFRV	Nitrogen fertilizer replacement value

Introduction

To mitigate climate change, greenhouse gas (GHG) emissions from the agricultural sector need to decrease. In this light, improving the efficiency of applied nitrogen (N) to crops is a promising avenue. When improving the efficiency of applied N, yields can be increased while reducing the losses to the environment. This leads to lower GHG emissions per kg yield, higher profitability for farmers, and potentially higher food security. Evidently, increasing agronomic N use efficiency (N-AE) of organic or mineral fertilizer should be a priority for agronomic research. In this working paper, N-AE is defined as the additional grain yield (kg) for a certain amount of N application, divided by that N application (kg).

In a previous working paper by Hijbeek et al. (2020) a methodology was explored for benchmarking N use efficiency and related GHG emissions. Afterwards, new insights were gained on the relation between N application, N-AE and attainable yields (van Grinsven et al., 2021; accepted). These insights showed that N-AE is highly dependent on the attainable yield for given circumstances. Based on this observed dependency, in this working paper we propose an alternative manner for N benchmarking.

The proposed benchmarking method relies on insights from long-term experiments using mineral fertilizer N application only. From a circularity perspective, it is beneficial to first (re-) use available organic amendments (such as manure or compost) and only then complement these with mineral fertilizers to fulfill crop nutrient requirements (de Boer and van Ittersum, 2018). Nevertheless, this will depend on the type of amendments and its N-uptake efficiency. While the application of mineral fertilizers can be attuned to enhance N uptake and reduce N losses, this is less so for organic amendments. Organic amendments on the other hand can improve soil fertility and water holding capacity by improving the soil structure and supply other (potentially deficient) nutrients and possibly increase water infiltration and water holding capacity, rootability, workability, organic carbon stocks or disease suppressiveness. As such, these two N sources could be used complementarily and increase each other’s use efficiency. If the crop N uptake from an organic amendment is however very low, it might be better used for an alternative purpose (such as feed or energy source) to prevent N losses to the environment. More insight is therefore needed into the N-uptake efficiency of different organic amendments and the extent to which organic amendments can enhance the efficiency of mineral fertilizer N use.

The crop N-uptake efficiency from organic amendments can be expressed as the Nitrogen fertilizer replacement value (NFRV), which is a comparison between the effectiveness of a kg N applied as organic amendment, compared to a kg N applied as mineral fertilizer. In this working paper, we explore the N efficiency of organic and mineral fertilizer N using two data sets on cereal experiments: one from Europe and one from Sub-Saharan Africa. Finally, using the same European data set, we assess if the N-AE of mineral fertilizer N can be improved adding organic amendments.

A new method to benchmark yield N response curves and agronomic N use efficiency

Based on principles used in the Quantitative Evaluation of the Fertility of Tropical Soils QUEFTS approach (Janssen et al., 1990), ten Berge et al. (2019) proposed a method to calculate long term minimum N-input requirements for target crop yields. The method presumes equilibrium between soil N status and annual N-input rate, as well as the returning of crop residues. It postulates that, at best, an annual N-input rate equal to the N uptake in total aboveground biomass suffices to attain the corresponding target yield. Hence the qualification ‘minimum nutrient requirement’. In addition, above authors presented a method to calculate local short term N input requirement, by combining N-AE observed in local field trials with soil N supply estimates inferred from national statistics on crop yields and fertilizer application. This ‘short-term’ method ignores the above conditions of soil equilibrium and return of crop residues.

In both above methods (short and long term), N-AE is presumed to decrease slightly with higher N input, but the response curve is unaffected by the level of potential or attainable yield. This implies that N requirement (N from soil and fertilizer) for a given target yield is similar for two locations, even when they have different potential or attainable yields. The above was considered reasonable at the time of publication, given that insufficient information was available for sub-Saharan Africa (SSA) to parameterize a possible dependence of N-AE on potential or attainable yield levels. This situation (insufficient SSA data) remains so today.

Nevertheless, recent work by van Grinsven et al. (2021; accepted) spurred further refinement of above approaches. The authors of the latter study combined a number of long-term trials to assess whether a generic (global) N – yield response curve for cereals could be formulated and, if so, what its shape would look like. The authors defined the top (or plateau) of the response curves - where yields are not limited by N supply - as the attainable yield (Y_{max}). This differs from the potential yield in a given location, which is the maximum yield estimated using crop growth models based on soil and climate data (van Ittersum and Rabbinge, 1997). Following, the authors defined the relative yield (Y_r) as the ratio between yield and Y_{max}.

Based on the extensive data set from global long-term trials, N-input requirements turned out to be more closely related to relative yields than to absolute yields. This implies a clear positive effect of Y_{max} on N-AE. The corresponding relation by van Grinsven et al. (2021; accepted) is expressed in Eq. 1, where Y is the grain yield expressed in kg/ha, Y_{max} is the attainable yield expressed in kg/ha and N_{av} is the available N (soil N supply combined with mineral fertilizer N application) expressed in kg N/ha. Here, soil N supply is estimated by extrapolating a yield N response curve to the left side of the x-axis, thereby expressing the crop N uptake in mineral fertilizer N equivalents.

$$Y = Y_{max} *(-0.0187 * N_{av}^2 + 8.768 * N_{av}) \qquad \text{(Eq. 1)}$$

Depending on the location, Y_{max} will be determined both by biophysical factors such as soil type and climate, and by agronomic management related aspects such as the crop variety, time of sowing, seed quality, weeding and pest and disease incidences.

For our current purposes (i.e., spatial differentiation and benchmarking of N input requirements for target yields), biophysical factors affecting Y_{max} can be collectively represented by a single parameter, namely water-limited yield potential (Y_w) as calculated by crop growth models from spatial biophysical data (van Ittersum et al., 2013). When the agronomic management is perfect, Y_{max} equals the Y_w value in the given location. Using this approach, observed response curves and N-AE values for a certain amount of N application can be compared to the theoretically best attainable values, by combining spatially differentiated Y_w value with the ‘generic response curve’ as proposed by van Grinsven et al. (2021; accepted). Using a selection of long term European experimental data collected by Hijbeek et al. (2017) for which water-limited yields (Y_w) could be derived from www.yieldgap.org, we made such comparisons for trials with maize, wheat or barley (Figure 1). In each of these trials, N treatments were always accompanied with sufficient P and K.

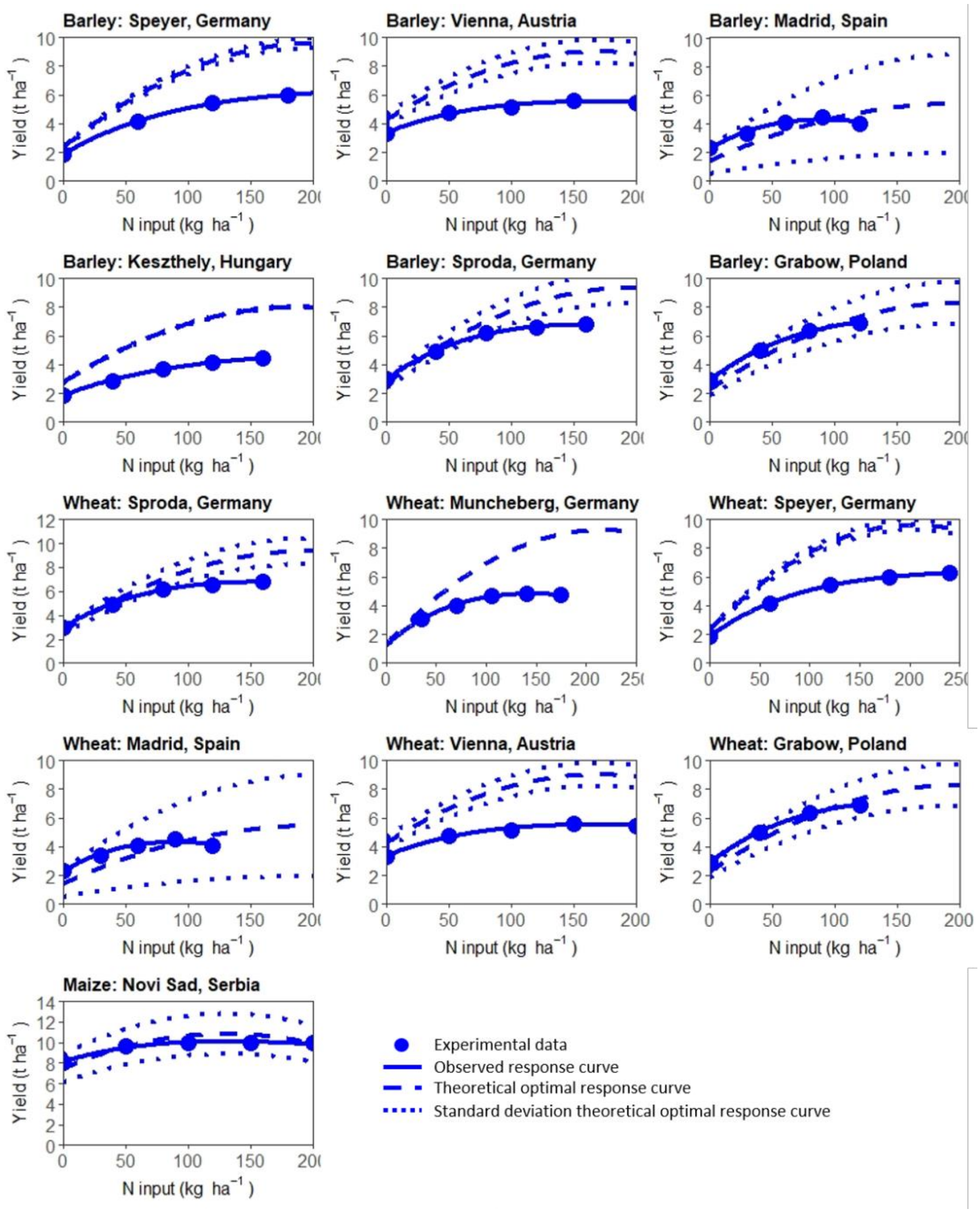

Figure 1. Observed and theoretical optimal response curves for wheat, maize, and barley in eight long-term experiments in Europe

Given a certain N application and potential yield, observed N-AE can thus be compared to the values they could theoretically reach. For each of the response curves in Figure 1, observed and theoretical potential N-AE at an application of 100 kg mineral fertilizer N/ha are calculated according to Equation 2.

$$NAE = \frac{yield_{NPK} - yield_{PK}}{N_{application}} \qquad \text{(Eq. 2)}$$

We further define the ratio between the attainable yield (observed plateau; Y_{max}) and the water-limited yield potential (modelled Y_w), as the 'degree of good agronomy'; the latter is also in included in Table 1.

Table 1. Overview of experiments included, crop types, potential yields, attainable yields, observed agronomic N use efficiencies (N-AE), potential N-AE and the ratio between the two

Experiment	Crop	Potential yield (t/ha)	Attainable yield (t/ha)	Degree of good agronomy[1] (-) agronomy (Y_{max} / Y_w)	Observed n-ae (Kg yield/kg N applied)[2]	Potential n-ae (Kg yield/kg N applied)[1]	Ratio observed and potential N-ae (-)
Grabow	Wheat	8.06	7.19	0.89	37.7	45.2	0.83
	Barley	6.15	3.86	0.63	15.3	31.4	0.49
Keszthely	Barley	7.79	4.88	0.63	20.6	40.7	0.51
Madrid	Wheat	5.30	4.31	0.81	20.2	30.1	0.67
	Barley	6.26	4.30	0.69	15.6	36.4	0.43
Muncheberg	Wheat	9.00	4.83	0.54	33.4	56.2	0.59
Novi Sad	Maize	10.54	10.09	0.96	19.0	31.8	0.60
Speyer	Wheat	9.33	6.33	0.68	32.0	53.8	0.60
	Barley	7.60	5.66	0.75	32.8	45.9	0.71
Sproda	Wheat	9.09	6.77	0.74	34.6	50.3	0.69
	Barley	7.82	2.74	0.35	6.9	29.8	0.23
Vienna	Wheat	8.77	5.53	0.63	19.3	39.5	0.49
	Barley	6.48	5.98	0.92	23.3	31.1	0.75

[1] *Degree of good agronomy is defined as attainable yield divided by water-limited potential yield (Ymax / Yw)*

[2] *AtAt 100 kg N/ha*

N use efficiency of organic vs mineral fertilizers

The presented generic response curve by van Grinsven et al. (2021; accepted) in the previous chapter is based on the application of mineral N fertilizer. To understand the N- input requirements when organic inputs are used instead of mineral fertilizers, one needs to quantify the Nitrogen Fertilizer Replacement Value (NFRV) of organic amendments (Schröder, 2005). The apparent NFRV of an organic amendment expresses the amount of mineral fertilizer N needed for the same yield relative to the amount of N applied as organic amendment. The NFRV at similar yield can thus be expressed by Eq. 3.

$$NFRV = \frac{N_{mineral\,fertiliser}\ to\ obtain\ Y}{N_{organic\,amendment}\ to\ obtain\ Y} \qquad \text{(Eq. 3)}$$

It can be argued that we should call the above ratio ‘apparent NFRV’, for it being based on equal yield instead of equal N uptake. In addition, it should be noted that other benefits from the amendment – rather than N – may be the cause of better crop performance and yield, included in the NFRV. In the remainder of the text, we keep to NFRV for brevity.

If the NFRV of an organic amendment is below 1, crops use N applied in mineral fertilizer more efficiently than N applied in the organic amendment in the years of application and measurement. If the NFRV is above 1, it is the other way around: N applied as organic amendment is used more efficiently than N applied as mineral fertilizer. If the NFRV is below 0 (i.e., a negative yield response to the amendment), plant available N is reduced due to N immobilization. This may be caused by the organic amendment immobilizing rendering it less available for crop uptake. NFRV values of organic amendments depend on a wide range of factors, such as the application method, soil, and climate (Schröder, 2005), but also on the chemical characteristics of the organic amendment (Delin et al., 2012) and the duration of application (Gutser et al., 2005). To optimize N application, farmers need to understand the NFRV of their organic amendment. Underestimation of NFRV of an organic amendment gives a risk of excess N application which can lead to environmental losses. Similarly, overestimation of the NFRV may lead to insufficient N application with adverse effect on yields.

In this paper, we compare the NFRV of different organic amendments across two continents (Europe and sub-Saharan Africa) for a range of organic amendment types. The European data is from Hijbeek et al. (2018) and the African data is from Gram et al. (2020).

Observed nitrogen fertilizer replacement values in European cereal experiments

Based on eight long-term cereal experiments across Europe, the variation in NFRV was calculated for farmyard manure (FYM), straw, and a combination of straw and green crop residues, both with and without mineral fertilizer N (at low and high N rates; Figure 2). All underlying field experiments were long term. The mean duration of the FYM treatments was 29 years, the mean experimental duration of the straw treatments was 34 years and the mean experimental duration for the combined application of straw and green crop residues was 11 years. NFRV was preferably determined as a mean value over the last two crop rotations for which data was available.

At low N supply, NFRV was 0.53 for FYM, 0.12 for straw and 0.14 for a combined application of straw and green crop residues (Figure 2a). Only for FYM was the NFRV significantly different from zero ($p < 0.0001$). At higher N supply (when organic amendments are applied in combination with mineral fertilizer N), the values for NFRV increased, but the variation also increased considerably (Figure 2b). For FYM, the mean NFRV was 1.13, for straw 0.35 and when straw was combined with green crop residues the mean NFRV was 0.94. There was no significant difference between the mean NFRV of the different organic amendments.

While in some cases, the NFRV approaches the value of 1 (having a similar efficiency of mineral fertilizer N), the majority of the observed NFRV was lower than 1 (Figure 2a, b).

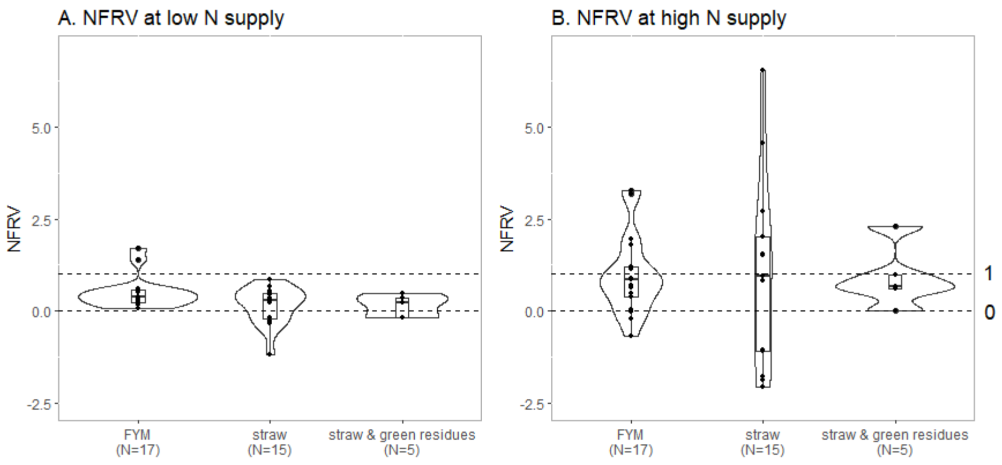

Figure 2. Boxplot of observed Nitrogen Fertilizer Replacement Value (NFRV) for FYM (farmyard manure), straw and straw & green crop residues at eight long-term European field experiments (N =38). Dashed lines refer to NFRV=0 and 1.

Observed nitrogen fertilizer replacement values in African maize experiments

Based on 20 short- and long-term maize field experiments across sub-Saharan Africa (Figure 3), NFRV was calculated for five types of organic amendments, namely three categories of crop residues (with different N, lignin or phenol content), sawdust and compost plus FYM (Table 2).

Figure 3. Map of Africa with sites of trials

Table 2. Classification of organic input for the data set from sub--Saharan Africa

Class	N content (%)	Lignin content (%)	Phenol content (%)	Origin of crop residues
Crop residue I	> 2.5	<15	<4	Cajanus cajan, Crotalaria juncea, Crotalaria ochroleuca, Gliricidia sepium, Glycine max, Lablab purpureus, Parkia biglobosa, Tithonia diversifolia
Crop residue II	> 2.5	>15	<4	Azadirachta indica, Calliandra calothyrsus, Leucaena leucocephala spp., Senna siamea, Mucuna pruriens
Crop residue III	<2.5	<15	NA	Arachis hypogaea, Brachystegia spiciformis, Coffee, Maize residues, Millet residue, Sorghum residue, Triticum aestivum
Sawdust	<2.5	>15	NA	-
Compost + Manure	NA	NA	NA	-

Mean NFRV were between 0 and 1 for crop residues type I and II and for compost and manure (0.4, 0.66 and 0.6 respectively). For crop residue type III and sawdust, the mean NFRV was negative (-0.69 and -3.3), indicating an immolization of N. For manure, the observed NFRV in sub-Saharan Africa was comparable to Europe but overall, observed variation was larger than for the European field experiments, with NFRV ranging between -5.3 and +4.7.

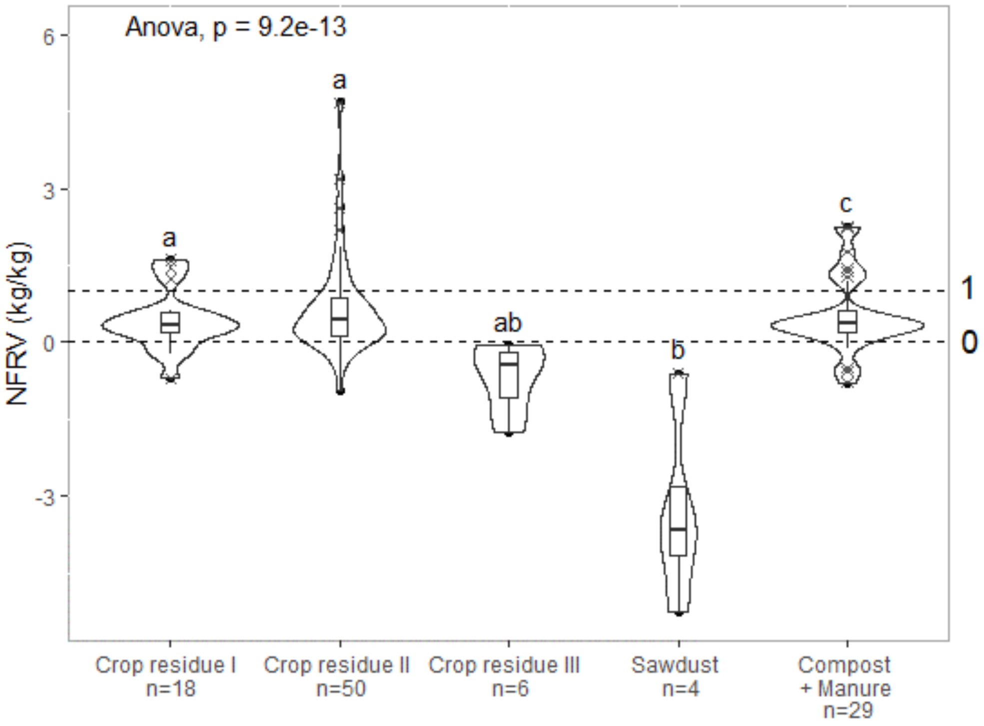

Figure 4. Boxplots of NFRV for different types of organic amendments (see Table 2) across 20 trials in sub-Saharan Africa, N = 107. Based on a subset of the underlying data from Gram et al (2020). Dashed lines refer to NFRV=0 and 1

After a longer duration, NFRV may increase due to residual N supply. As the underlying experiments from sub-Saharan Africa contained both short and long-term trials, we assessed whether a time-effect could be found (Figure 5). No significant difference was found between the different experiment durations (p=0.54).

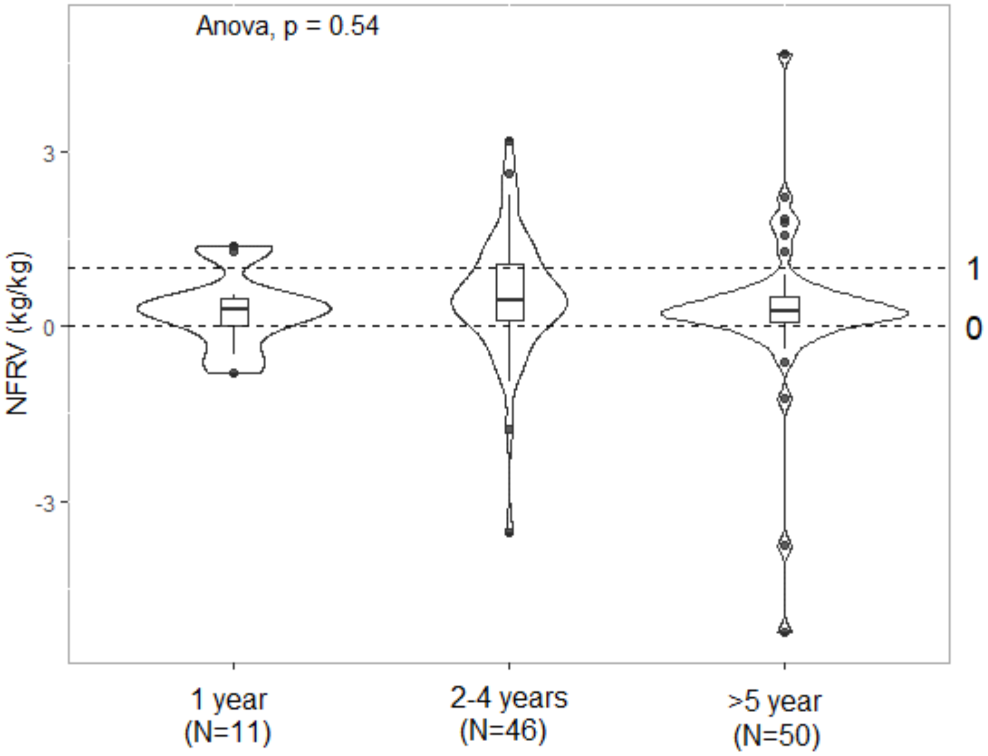

Figure 5. Observed NFRV after different time periods across 20 trials in sub-Saharan Africa, N = 107. Based on a subset of the underlying data from Gram et al (2020). Dashed lines refer to NFRV=0 and 1.

Influence of organic amendments on agronomic use efficiency of mineral fertilizer N

Integrated Soil Fertility Management (ISFM) promotes the combined use of organic and mineral fertilizers to enhance synergistic effects (Palm et al., 1997; Vanlauwe et al., 2010). One way to assess if indeed such synergistic effects exist, is to assess whether the use of organic amendments increases the N-AE of mineral fertilizer N. Thus, a comparison between the N-AE of mineral fertilizer N with and without organic amendments is needed. This comparison can be done either at similar yield levels, or at similar N rates (Figure 6). In this study, we used both methods and compared the outcomes.

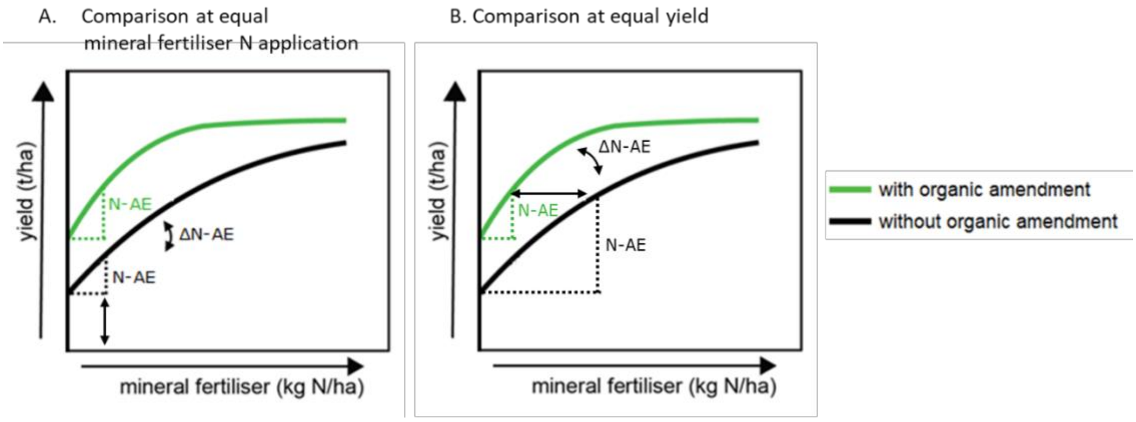

Figure 6. Conceptual illustration of comparing agronomic N use efficiency (N-AE) with and without organic amendments at equal mineral fertilizer N application (A) or at equal yields (B)

The analysis was performed on a similar European dataset of long-term experiments (Hijbeek et al 2017), focusing on cereals. At an application rate of 50 kg mineral fertilizer N/ha, the N-AE of mineral fertilizer was found to be 31.33 kg additional grain yield per kg N applied. This N-AE decreased on average 17.3% when the mineral fertilizer N was applied together with organic amendments (such as FYM, slurry, straw, or a combination of straw and green crop residues; Table 3).

Table 3. Change in N-AE of mineral fertilizer-N for cereals (maize, barley, wheat and rye) when mineral fertilizers at rate of 50 kg N/ha are combined with organic amendments.

Organic amendment	N-AE without organic amendment (Additional kg grain yield/kg N)	N-AE with organic amendment (Additional kg grain yield/kg N)	Δ N-AE (%)	p-value (t.test)	sample size (N)
FYM	30.50	24.03	-18.14	0.06	32
Slurry	31.43	23.31	-29.84	0.25	10
Straw	28.57	23.68	-17.08	0.35	18
Straw and green crop residues	35.64	31.63	-10.94	0.28	20
Across all amendment types	*31.33*	*25.76*	*-17.26*	***0.01***	*80*

The comparison at similar mineral fertilizer N rates is not completely fair as the total available N will be larger when organic amendments are added (Figure 6A). As such, the decrease in N-AE when organic amendments are added may be due to diminishing returns at higher total N supply. We therefore also assessed the change in N-AE at similar yields (i.e., the N-AE was assessed at a similar yield level when mineral fertilizer N was applied either with or without organic amendment).

Table 4. Change in N-AE (of mineral fertilizer-N) for cereals (maize, barley, wheat and rye) when mineral fertilizers are combined with organic amendments, assessed at similar yield levels.

Organic amendment	N-AE without organic amendment (Additional kg grain yield/kg N)	N-AE with organic amendment (Additional kg grain yield/kg N)	Δ N-AE (%)	p-value (t.test)	sample size (N)
FYM	38.61	35.65	-6.52	0.53	32
Slurry	42.09	39.44	-10.11	0.76	7
Straw	40.64	35.32	-20.15	0.52	19
Straw and green crop residues	40.16	39.50	-3.88	0.87	20
Across all amendment types	*39.81*	*36.90*	*-9.49*	*0.33*	*78*

When assessed at similar yield level, the N-AE of mineral fertilizer N application does not significantly change when combined with an organic amendment (Table 4). When comparing the N-AE at equal yield however, the control yield (without N application) may be lower for the mineral fertilizer only treatments, possibly leading to a higher N-

AE value (Figure 6B). Assessing the marginal N-AE (slope of the response curve) at equal yield levels might therefore be a next methodological improvement, which we will take in a next step.

Conclusion and recommendations

In this working paper we have presented ongoing work on monitoring, benchmarking, and improving the efficiency of different N sources, either as mineral fertilizers or as organic amendments, with the aim to increase our understanding on how N can be used at highest efficiency to produce cereals with minimum GHG emissions.

We have shown that it is possible to benchmark observed yield – N response curves in different locations with a theoretically best curve, using a generic response curve and potential yield. This method might be useful to explore where current N-AE values are low, based on the amount of N applied, and identify where (geographically) the largest potential for improvements in agronomy of the crop may be situated. A limitation of the proposed approach is the required data on soil N supply, potential yield and attainable yields. Currently, this information is sparsely available which might be a barrier for uptake of this method.

We have also shown that N supplied by mineral fertilizers is taken up more efficiently by cereals than from organic sources, with variation depending on the type of organic amendment. Variation was larger for sites in Africa than Europe, which makes targeted fertilizer strategies less straightforward. In further work, we aim to investigate which factors drive this variability.

Finally, we have shown that combining organic amendments with mineral fertilizer does not increase the N-AE of the mineral fertilizer N, or at least not so in Europe, perhaps due to the increased total N availability leading to diminishing returns. In future research, we aim to disentangle effects of organic amendments on the efficiency of mineral fertilizer N use, while extending our analysis to tropical regions.

References

de Boer, I.J., van Ittersum, M.K. 2018. Circularity in agricultural production, Mansholt lecture. Wageningen University and Research, Wageningen.

Delin, S., Stenberg, B., Nyberg, A., Brohede, L. 2012. Potential methods for estimating nitrogen fertilizer value of organic residues. *Soil Use and Management* 28, 283-291.

Gram, G., Roobroeck, D., Pypers, P., Six, J., Merckx, R., Vanlauwe, B. 2020. Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: A meta-analysis. *PLoS ONE* 15, e0239552.

Gutser, R., Ebertseder, T., Weber, A., Schraml, M., Schmidhalter, U. 2005. Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land. Z. Pflanzenernähr. Bodenk. 168, 439-446.

Hijbeek, R., ten Berge, H.F.M., Whitmore, A.P., Barkusky, D., Schröder, J.J., van Ittersum, M.K. 2018. Nitrogen fertilizer replacement values for organic amendments appear to increase with N application rates. *Nutrient Cycling in Agroecosystems* 110, 105-115.

Hijbeek, R., van Ittersum, M.K., ten Berge, H.F.M., Gort, G., Spiegel, H., Whitmore, A.P. 2017. Do organic inputs matter – a meta-analysis of additional yield effects for arable crops in Europe. *Plant and Soil* 411, 293-303.

Hijbeek, R., van Loon, M., van Ittersum, M., ten Berge, H. 2020. Benchmarking crop nitrogen requirements, nitrogen-use efficiencies and associated greenhouse gas mitigation potential: Methodology exploration for cereal production in sub-Saharan Africa.

Janssen, B.H., Guiking, F., Van der Eijk, D., Smaling, E., Wolf, J., Van Reuler, H. 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma* 46, 299-318.

Palm, C.A., Myers, R.J., Nandwa, S.M. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. *Replenishing soil fertility in Africa*, 193-217.

Schröder, J. 2005. Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. *Bioresource technology* 96, 253-261.

ten Berge, H.F.M., Hijbeek, R., van Loon, M.P., Rurinda, J., Tesfaye, K., Zingore, S., Craufurd, P., van Heerwaarden, J., Brentrup, F., Schröder, J.J., Boogaard, H.L., de Groot, H.L.E., van Ittersum, M.K. 2019. Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Global Food Security* 23, 9-21.

van Grinsven, H.J., Ebanyat, P., Glendining, M., Gu, B., Hijbeek, R., Lam, S.K., Lassaletta, L., Mueller, N.D., Pacheco, F.S., Quemada, M., W. Bruulsema, T., Jacobsen, B.H., ten Berge, H.F. 2021; accepted. Establishing long-term nitrogen response of global cereals to assess sustainable fertilizer rates. *Nature Food*.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z. 2013. Yield gap analysis with local to global relevance—a review. *Field Crops Research* 143, 4-17.

van Ittersum, M.K., Rabbinge, R. 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Research* 52, 197-208.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D. 2010. Integrated soil fertility management operational definition and consequences for implementation and dissemination. *Outlook on agriculture* 39, 17-24.

CGIAR

RESEARCH PROGRAM ON
Climate Change,
Agriculture and
Food Security

CCAFS

The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) brings together some of the world's best researchers in agricultural science, development research, climate science and Earth system science, to identify and address the most important interactions, synergies and tradeoffs between climate change, agriculture and food security. For more information, visit us at **https://ccafs.cgiar.org/.**

Titles in this series aim to disseminate interim climate change, agriculture and food security research and practices and stimulate feedback from the scientific community.

CCAFS is led by:

Alliance

Bioversity International

CIAT
International Center for Tropical Agriculture
Since 1967 Science to cultivate change

CCAFS research is supported by:

CGIAR
Science for a food-secure future

Australian Government
Australian Centre for International Agricultural Research

Irish Aid
An Roinn Gnóthaí Eachtracha agus Trádála
Department of Foreign Affairs and Trade

Ministry of Foreign Affairs of the Netherlands

NEW ZEALAND
FOREIGN AFFAIRS & TRADE
Aid Programme

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development
and Cooperation SDC

UKaid
from the British people

USAID
FROM THE AMERICAN PEOPLE

IFAD
Investing in rural people