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The state of cropland nitrous oxide emission research in Sub-Saharan Africa

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Nitrous oxide (N_2O) emissions from cropland soils are a significant source of greenhouse gases in Sub-Saharan Africa (SSA), yet fluxes and drivers remain poorly quantified. This review synthesizes findings from 39 field-based studies across Sub-Saharan Africa to assess current knowledge, key drivers, and research gaps. Additionally, this review offers a focused analysis on the effect of nitrogen fertilizer application on N_2O emissions. The main finding is that emissions were strongly influenced by nitrogen input rates, precipitation, cropping systems, soil types, and measurement durations. Emission factors often diverge from IPCC Tier 1 defaults, suggesting the need for context-specific values. However, research is unevenly distributed: Studies from Kenya dominate the literature, while large areas, especially in Central Africa, lack data. Methodological inconsistencies further limit comparability across studies. We identify priorities for future research, including geographic expansion, standardized protocols, and improved integration of climate and agronomic variables. Strengthening the regional evidence base is essential for accurate inventories and for developing climate-smart agricultural policies tailored to SSA's diverse agroecosystems.

KEYWORDS

cropland soils, emission factors, fertilizer induced emissions, mitigation, nitrous oxide

1 Introduction

Nitrous oxide (N_2O) is a potent greenhouse gas (GHG), with a global warming potential (GWP) approximately 273 times greater than carbon dioxide (CO_2) over a 100-year period (Intergovernmental Panel On Climate Change, 2023) and it is currently the most important ozone-depleting gas (Ravishankara et al., 2009). In soils, N_2O is primarily produced through two biological processes, nitrification and denitrification, with nitrification depending on ammonium NH_4^+ and oxygen (O_2) availability, while denitrification depends on nitrate (NO_3^-), degradable organic matter, and O_2 limitation. These processes are mainly controlled by soil properties, agricultural management practices, microbial communities and environmental conditions such as soil moisture and temperature and the availability of organic carbon and nitrogen (N) in the soil (Butterbach-Bahl et al., 2013; Della Chiesa et al., 2019; Cui et al., 2024; Piñeiro-Guerra et al., 2025). Agriculture is the largest source of anthropogenic N_2O emissions, accounting for approximately 60% of the global total—rising from 2.2 (1.6–2.8) Tg N yr^{-1} in 1980 to 3.9 (2.9–5.1) Tg N yr^{-1} in 2020 (Syakila and Kroeze, 2011; Tian et al., 2024). Within this agricultural share, croplands, largely driven by synthetic and organic N additions, contribute around one-third of total anthropogenic N_2O emissions (Tian et al., 2023). The remaining agricultural emissions primarily originate from livestock systems, including manure management and grazing-related emissions.

N_2O emissions from croplands in Sub-Saharan Africa (SSA), alongside other GHGs are projected to rise in the coming decades, driven by increasing use of resource inputs, particularly N fertilizers and organic amendments (Hickman et al., 2014; Tongwane and Moeletsi, 2018; Zheng et al., 2019). SSA is home to over 1.26 billion people (World Bank, 2024), approximately 13% of the global population and faces significant challenges in achieving food security (McGuire, 2015). This rapidly growing population is expected to drive up greater use of synthetic N fertilizers and manure to meet rising food demand, which is expected to lead increase N_2O emissions in the region (Leitner et al., 2020). Given the limited availability of land and ongoing soil degradation, efforts in SSA are increasingly focused on intensifying production and improving yields through strategies such as increasing fertilizer use and enhancing crop nutrient use efficiency (Vanlauwe and Dobermann, 2020; Jayne and Sanchez, 2021).

Currently, N fertilizer use in SSA countries are considered the lowest globally, with an average application rate stagnating between 13 and 20 kg N ha^{-1} (Dimkpa et al., 2023) resulting in negative soil nutrient balances and large yield gaps (Mueller et al., 2012). To address this challenge, regional agricultural policies recommend doubling the use of mineral fertilizers, with some studies within the region recommending raising fertilizer application rates to levels of 50 Kg-N ha^{-1} particularly in areas with inherently poor soils as part of a broader effort to boost crop productivity and ensure food security (Koussoubé and Nauges, 2016; Tongwane and Moeletsi, 2018). Although such measures aim to close the yield gap and improve soil fertility, there is a risk of increased GHG emissions, particularly N_2O emissions. Calls to increase fertilizer use like those of the "2006 Abuja Declaration on Fertilizer for the African Green Revolution" (African Union, 2006), led by the African Union member states as well as the "2024 Nairobi Declaration on Africa Fertilizer and Soil Health Summit" which aim to set up regional policies for improved agricultural production, have raised concerns about potentially reduced nitrogen use efficiency (NUE) and the possibility for greater environmental harm through processes such as leaching (Vanlauwe et al., 2023). However, it is important to consider these concerns in light of yield-scaled emissions. Evidence suggests that when fertilizer rates are increased within a reasonable agronomic threshold (approximately 120-150 Kg-N ha^{-1}), yield scaled N_2O emissions often decrease, since higher yields compensate for the rise in absolute emissions (Leitner et al., 2020). From a land use perspective, intensifying fertilizer use on existing cropland can be preferable to expanding cultivation into new areas, which will typically result in lower crop producing croplands with high yield scaled emissions. Moreover, insufficient fertilization can lead to soil nutrient mining and the depletion of soil organic carbon (SOC) stocks, further contributing to greenhouse gas emissions (Van Loon et al., 2019).

Research has shown that intensification efforts, particularly for staple crops like maize (Zea mays L), could potentially lead to major increases in N_2O emissions from soils (while reducing yield-scaled emissions), highlighting the need for yield improvement strategies that also consider environmental sustainability (Leitner et al., 2020). For SSA, the socioeconomic and environmental situation necessitates a delicate balance between food security and mitigation of N pollution, particularly N_2O production. This requires a clear understanding of N cycling and N_2O emission mechanisms, to allow accurate assessment of emission levels and development of strategies to ensure a sustained food supply (Rosenstock et al., 2013; Bodirsky et al., 2014; Kim et al., 2021; Zhang et al., 2024).

Cropland N_2O emissions from SSA are currently underrepresented in global GHG datasets. This is primarily due to the limited number of field studies conducted in the region, hence limiting the activity data for national inventories (Perez-Quezada et al., 2023). In addition, limited access to proper infrastructure hinders study replications and extensive analysis on the effects of different farming practices. As a result, most countries in the region continue to rely on Tier 1 emission factors provided by the Intergovernmental Panel on Climate Change (IPCC) for their national GHG inventories, which are largely based on data from temperate ecosystems and may not accurately reflect conditions in SSA (Hickman et al., 2015; Butterbach-Bahl et al., 2016; Tian et al., 2023; Tully et al., 2023). Previous research suggests that default approaches may overestimate emissions (Zheng et al., 2019). Additionally, a methodological challenge persists in the way different studies quantify soil N_2O emissions, with variations in measurement approaches and data analysis leading to potential biases in data. Furthermore, knowledge gaps also arise from variations in fertilizer use, rainfall patterns, temperature, and soil types across the region, highlighting the need for localized data to better understand the drivers of emissions (Butterbach-Bahl et al., 2013).

Considering the knowledge gaps regarding N_2O emissions and processes in SSA, and the uncertainty in current methods to quantify emissions, this review seeks to:

1. Analyze the current state of knowledge and key drivers of cropland N_2O emissions in SSA
2. Assess N_2O accounting and data comparability across studies and countries in SSA, supporting more accurate emissions inventories.

Abbreviations: SSA, Sub-Saharan Africa; GHG, greenhouse gas; GWP, global warming potential; IPCC, Intergovernmental Panel for Climate Change; N, nitrogen; NUE, nitrogen use efficiency; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; MAT, mean annual temperature; MAP, mean annual precipitation; SOC, soil organic carbon; HTML, Hypertext Markup Language; EF, Emission Factors; WFPS, water-filled pore space; USDA, U.S. Department of Agriculture; IITA, International Institute of Tropical Agriculture; CIMMYT, International Maize and Wheat Improvement Center; ILRI, International Livestock Research Institute; CT, conventional; MT, minimum tillage; NT, no-tillage; DNDC, DeNitrification DeComposition.

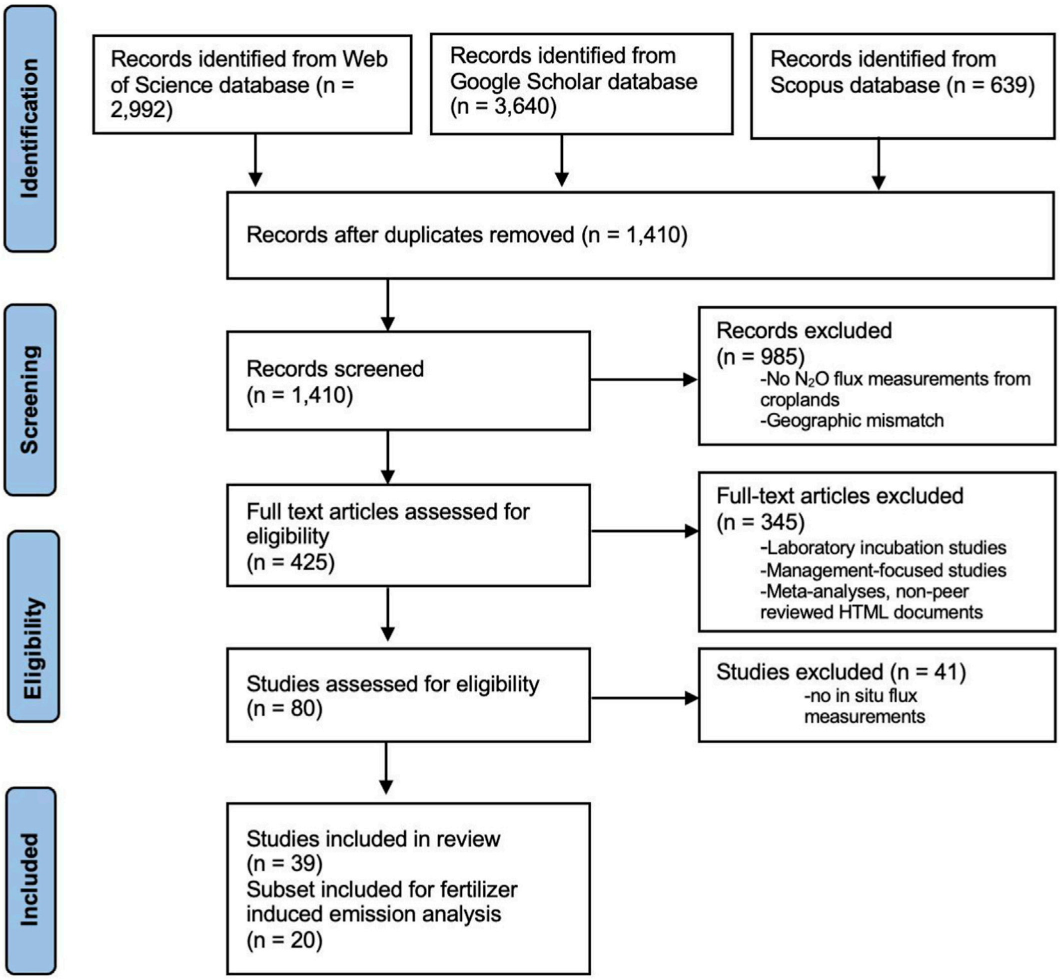

FIGURE 1
Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram for this review of cropland N_2O emissions from sub-Saharan Africa.

3. Support the development of predictive models and identify scalable mitigation strategies, ultimately informing climate-smart agricultural policies.

2 Methodology

2.1 Literature search and study selection

A systematic search was conducted across major academic databases, including Google Scholar, Web of Science, and Scopus, using the keywords “nitrous oxide emissions”, “cropping systems”, “emission factors”, and “Sub-Saharan Africa”. These platforms were chosen for their extensive collections of peer-reviewed articles, ensuring access to high-quality research. Unlike previous meta-analyses, our approach explicitly included cropping systems, fertilizer use, and soil properties, broadening the scope of the search. We adopted the Intergovernmental Panel of Climate Change (IPCC, 2006a) definition of cropland, which includes arable and tillable land, rice fields, and agroforestry systems not classified as forest. From the initial screening, 1,410 studies were selected (Figure 1), of which 39 met the criteria for inclusion in the final analysis. A further subset of 20 studies was retained for fertilizer-specific comparisons, as these provided explicit fertilizer treatment data. Articles were systematically excluded due to the following reasons: i) Lack of focus on N_2O emissions–many papers mentioned nitrogen cycling, soil health, or greenhouse gases broadly but did not report specific N_2O flux measurements; ii) Absence of *in situ* measurements–some studies modeled emissions or relied on literature reviews rather than direct field measurements; iii) Study type exclusions–laboratory incubation studies, management-focused studies whose primary aim was to test or evaluate specific management interventions designed to reduce N_2O emissions, rather than to measure baseline or typical emissions under standard agricultural practices, meta-analyses, non-peer-reviewed HTML documents and geographic mismatch.

After applying these filters, 39 studies spanning 13 countries remained (covering the years 2004–2025), all of which either reported *in situ* annual N_2O emissions or provided sufficient data for unit conversion-based estimation (see Annex 2). These studies covered diverse cropping systems and soil types, with data spanning from 1999 to 2025 (no date restrictions were applied to maximize inclusion). As climate data was not explicitly reported in many studies, mean annual temperature (MAT) was sourced from WorldClim 2.1 (Fick and Hijmans, 2017) and mean annual precipitation (MAP) from CHIRPS (Funk et al., 2015) with an average for the year range of 2000–2020.

The extracted and compiled dataset included:

- N_2O fluxes and associated emission values.
- Experimental and environmental properties–soil type, cropping system, rainfall, soil temperature, fertilizer treatment levels, fertilizer type, soil texture (clay/silt/sand composition), measurement duration, and geographic coordinates.
- Climate data–MAT and MAP.

2.2 Subset of N-fertilizer-induced N_2O emissions

For a focused analysis on the effect of N fertilizer application on N_2O emissions, a subset of studies was extracted from the full review database. Studies were included in this subset if they explicitly reported fertilizer-induced N_2O fluxes or emission factors, or if they presented treatment comparisons between fertilized and unfertilized plots. This subset was used to evaluate emission responses to different nitrogen input levels. This selection resulted in 20 studies with comprehensive data (see Annex 3).

2.3 Data analysis

Data on annual N_2O emissions were standardized to kg N_2O-N ha^{-1} yr^{-1} to facilitate cross-study comparisons. Extreme high values were inspected and retained unless they were clearly attributable to measurement or reporting errors. To address skewness, variance-robust statistical approaches were applied. In most cases, means were reported because they capture the full contribution of episodic pulses that often dominate annual N_2O totals in SSA and are consistent with inventory-oriented reporting (IPCC, 2006b), In some cases, medians were used, for example, when sample sizes were very small or when distributions were highly skewed to provide a robust summary less influenced by outliers. Where studies reported annual totals, we used those values directly. For studies in multi-cropping systems that provided season level measurements for all seasons, seasonal fluxes were summed to obtain an annual total. For studies that reported only a single season in regions known to have multiple cropping seasons, we treated those observations as seasonal. Where possible, data were aggregated by region, crop type, or fertilizer treatment to identify broad trends. Averages, medians, and ranges of emission estimates were calculated to highlight variability across studies. Statistical analyses were conducted to explore relationships between N_2O emissions and key drivers such as fertilizer application rates, soil properties, and climatic conditions. To determine the most suitable data-fitting models, we evaluated a range of approaches, including linear, nonlinear, natural log, and logarithmic models. Model selection was based primarily on the Akaike Information Criterion (AIC), which provides a robust framework for comparing models by balancing goodness of fit with model complexity and penalizing additional parameters. Statistical significance was set at a 5% critical level. For the regression analyses of N_2O fluxes across treatments, model assumptions of homoscedasticity and normality were evaluated using residual diagnostics. Where the raw data exhibited skewness or non-constant variance, log or natural log transformations were applied to stabilize the variance and improve normality. The best-fitting model for the dataset was selected based on statistical robustness and interpretability in the context of the research question. All statistical analyses were performed using the R software to ensure the robustness of the results (R Core Team, 2024).

3 Results and discussion

3.1 Current understanding of N_2O emissions in SSA

Our estimate of SSA's average total cropland N_2O emission is considerable, estimated at 0.24 ± 0.028 Tg N_2O-N yr^{-1} based on a total cropland area of 322.63 million ha across nine countries that reported emission factors (Annex 4). This constitutes up to 20% of cropland global emissions, estimates which have increased roughly 1-3 times in the last decades, ranging from 0.4–1.4 Tg N_2O-N yr^{-1} in the 1960s to 1.3–3.3 Tg N_2O-N yr^{-1} in the 2010s (Tian et al., 2019; Wang et al., 2020; Xu et al., 2020). In our analysis, the average area-weighted cropland N_2O emission was estimated at 0.73 ± 0.09 kg N_2O-N ha^{-1} yr^{-1} with values ranging from 0 to 2.76 kg N_2O-N ha^{-1} yr^{-1} across all site-year combinations. This estimate excludes vegetable systems, which often exhibit disproportionately high emissions due to intensive fertilization and greenhouse cultivation, despite covering relatively small land areas. This compared to 1.24 kg N_2O-N ha^{-1} yr^{-1} the average total N_2O emissions reported for SSA (Tian et al., 2023). While high-emitting regions globally, such as the North China Plain, Ganges Basin, Saudi Arabia, and parts of Western Europe report emissions exceeding 4 kg N_2O-N ha^{-1} yr^{-1} due to fertilizer inputs that go above 350 kg N ha^{-1} yr^{-1} in some regions, SSA's agricultural systems are characterized by much lower N inputs, typically under 50 kg N ha^{-1} yr^{-1} (Masso et al., 2017; Elrys et al., 2020). Despite the relatively low synthetic N inputs and direct emissions, SSA's total N_2O emissions remain notable due to the region's vast cropland area. Emission Factors (EFs) across SSA are highly variable, ranging from 0.01% to 4.1% and observed emissions (including vegetables) span from as low as 0.01 up to 113.4 kg N_2O-N ha^{-1} yr^{-1} reflecting the diversity of agro-ecological conditions and management practices.

The 39 studies compiled in this review span several countries in SSA (Figure 2), with Kenya having the highest representation, contributing 18 studies in 16 locations (Table 1). Measurement durations ranged from as short as 21 days to as long as 3 years. A significant portion (63%) of studies measured annual N_2O fluxes, typically spanning 12 months or more, with an average duration of 16.4 months. Seasonal flux studies (32.6%) focused on growing seasons, ranging from 2 to 9 months, with an average duration of 5.5 months. Short-duration studies (4.3%) were relatively uncommon, lasting only a few weeks to under 2 months (Annex

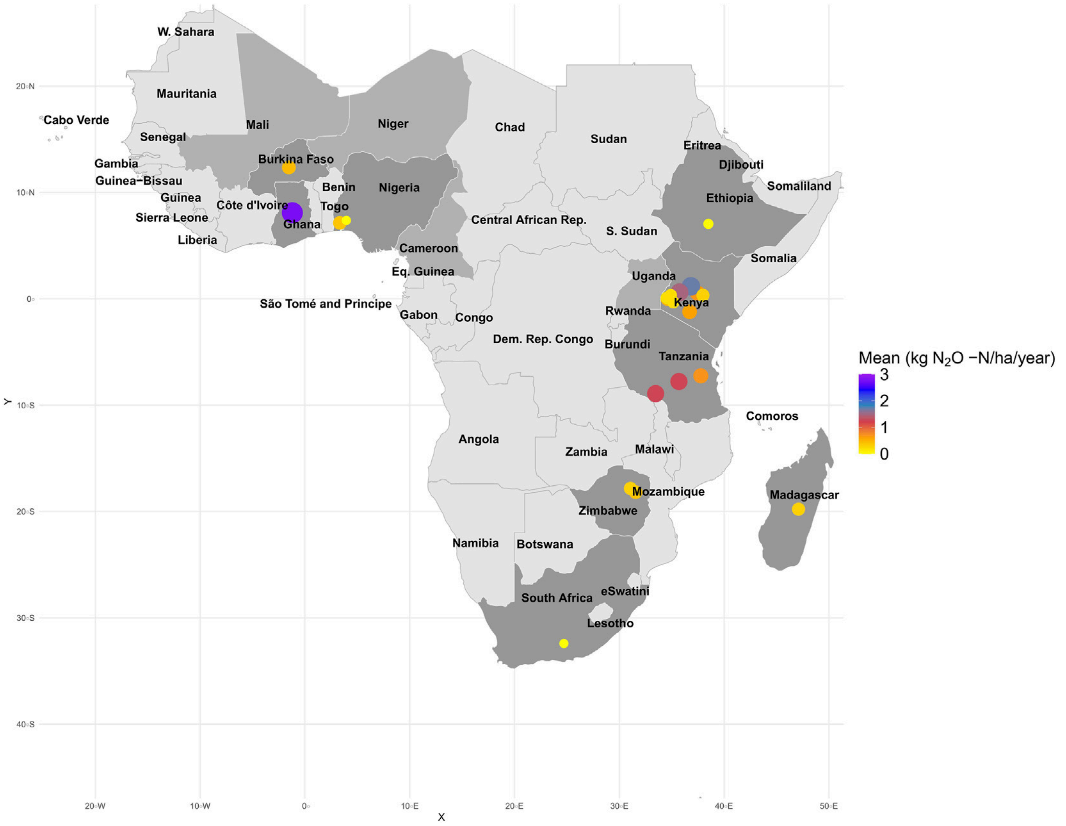

FIGURE 2
Study distribution of cropland nitrous oxide emission measurements and reported mean annual emission estimates across Sub-Saharan Africa. Vegetable studies were excluded because their exceptionally high N_2O emissions distorted the scale and obscured patterns among other crops. Layered visualizations: light grey: All SSA countries, medium grey: countries with N_2O field studies but no reported fertilizer induced emissions, dark grey: countries reporting fertilizer induced emissions. Circles represent the study locations and the size and color of the circle represents the magnitude of mean annual emissions (kg N_2O-N ha-1 yr-1).

2). Between 1999 and 2008, studies tended to be short-term in nature. From 2009 onwards, there was a clear shift toward multi-year studies. After 2020, studies increasingly cover 12 months and more, likely due to advancements in research methodologies and automation, as well as greater funding availability.

Sampling frequency varied extensively across studies. The most common frequency was weekly, reported in 6 studies, followed by daily measurements in another 6 studies. A few studies report measurements twice per week (2 studies), and some are event-based, with measurements taken following specific agricultural events such as fertilization (4 studies). Monthly measurements are less common, with 3 studies using this frequency. From a sub-sample of N_2O emissions from maize we sought to assess if there was any effect of length of measurements. Figure 3 illustrates how the duration of N_2O emission measurements influence the reported emission estimates. Studies categorized by study duration reveal clear differences in mean emissions (kg N_2O-N ha^{-1} yr^{-1}).

Studies that measured annual fluxes tend to report higher and more variable emissions than seasonal or short-term studies, likely because they capture key off-season pulses or episodic rainfall-triggered events that shorter studies miss. In contrast, seasonal and short-duration studies, which often cover only the cropping period or a few months, show lower median emissions and reduced variability. A Kruskal–Wallis test comparing emissions between short-term/seasonal studies (≤1 season) and long-term studies (≥1 year) indicated a trend toward higher emissions in long-term studies ($\chi^2 = 3.24$, df = 1, $p = 0.072$), though the difference was not statistically significant. While our dataset does not allow us to quantify the extent of potential underestimation due to the limited number of replicates, the contrast between growing-season and annual emissions observed in other studies (Ortiz-Gonzalo et al., 2018; Shumba et al., 2023; Zheng et al., 2023) suggests that restricting measurements to short timeframes may risk missing emissions occurring outside peak periods. Therefore, longer-term monitoring could help improve understanding of the full emission dynamics, especially in rainfed systems with high temporal variability. A limitation of our analysis is that annualization did not account for differences between single and double cropping systems. As a result, comparisons of annualized emissions across countries may be biased, with multi-season systems appearing to emit more simply due to the additional fertilization events. Future work should separate seasonal emissions or use yield-scaled metrics to allow for more balanced comparisons across contrasting cropping systems.

TABLE 1 Distribution of cropland N_2O emissions studies from SSA by country, location and year of measurements. Distribution of cropland N_2O emissions studies from SSA by country, location and year of measurements. Countries missing data: Angola, Benin, Burundi, Central African Republic, Chad, Congo, Dem. Rep., Congo, Rep., Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Gabon, Gambia, The, Guinea, Guinea-Bissau, Lesotho, Liberia, Libya, Malawi, Mauritius, Mozambique, Namibia, Rwanda, Senegal, Sierra Leone, Somalia, South Sudan, Sudan, Togo, Zambia.

Region	Country	No. of studies	No. of locations	1st year of measurements	Last year of measurements	Fertilizer effect studies with treatment level data provision	Average emissions by country and unit (averages are only reported for countries with sufficient replicates; other countries show individual study values)		Frequency of measurements
Central Africa	Cameroon	1	1	2020	2020		0.97	kg ha^{-1} yr^{-1}	2 times per month (1)
East Africa	Ethiopia	1	1	2015	2016		0.03	kg ha^{-1} yr^{-1}	Weekly (1)
	Kenya	18	16	1999	2020	11	0.81	kg ha^{-1} yr^{-1}	Daily (3), weekly (4), 1–3 days per week (1), weekly then biweekly (1), daily, weekly then biweekly (1), daily to weekly or monthly (1), 3 times per month (1), following key events and biweekly (1), 1-2 times per week (1), 2 times a week during rainy season, 2 weeks after fertilization then weekly (1), weekly after key events and biweekly during the off season (1), 1-2 times per week (1),2 days following each fertilization event (1)
	Tanzania	4	4	2012	2017	1	1.183	kg ha^{-1} yr^{-1}	Daily (2), not disclosed (1), weekly (1), weekly to monthly (1)
	Uganda	1	1	2018	2018		5.2	μg m^{-2} h^{-1}	4-5 times per month (1)
Southern Africa	South Africa	1	1	2018	2019		0.2	μg ha^{-1} day^{-1}	Daily (1)
	Madagascar	1	1	2006	2007	0	0.3	kg ha^{-1} yr^{-1}	Weekly (1)
	Zimbabwe	6	5	2000	2023	4	3.22	kg ha^{-1} yr^{-1}	Weekly (1), during rainy season (1), biweekly (2), not disclosed (1)

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TABLE 1 (*Continued*) Distribution of cropland N_2O emissions studies from SSA by country, location and year of measurements. Distribution of cropland N_2O emissions studies from SSA by country, location and year of measurements. Countries missing data: Angola, Benin, Burundi, Central African Republic, Chad, Congo, Dem. Rep., Congo, Rep., Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Gabon, Gambia, The, Guinea, Guinea-Bissau, Lesotho, Liberia, Libya, Malawi, Mauritius, Mozambique, Namibia, Rwanda, Senegal, Sierra Leone, Somalia, South Sudan, Sudan, Togo, Zambia.

Region	Country	No. of studies	No. of locations	1st year of measurements	Last year of measurements	Fertilizer effect studies with treatment level data provision	Average emissions by country and unit (averages are only reported for countries with sufficient replicates; other countries show individual study values		Frequency of measurements
West Africa	Burkina Faso	2	3	2006	2009	1	96.95*	kg ha^{-1} yr^{-1}	1–3 per week (1), twice a day (1)
	Ghana	1	1	2013	2014	1	2.76	kg ha^{-1} yr^{-1}	Daily during fertilization, then weekly (1)
	Nigeria	2	2	2000	2019	2	0.2	kg ha^{-1} yr^{-1}	Weekly (1), 1–3 days to 2 weeks (1)
	Mali	1	1	2004	2005		1.2	kg ha^{-1} yr^{-1}	Monthly (1)
	Niger	1	1	2006	2007		70*	kg ha^{-1} yr^{-1}	Twice a day for 6 days (1)
Total	13	39				20			

*Emissions from vegetables.

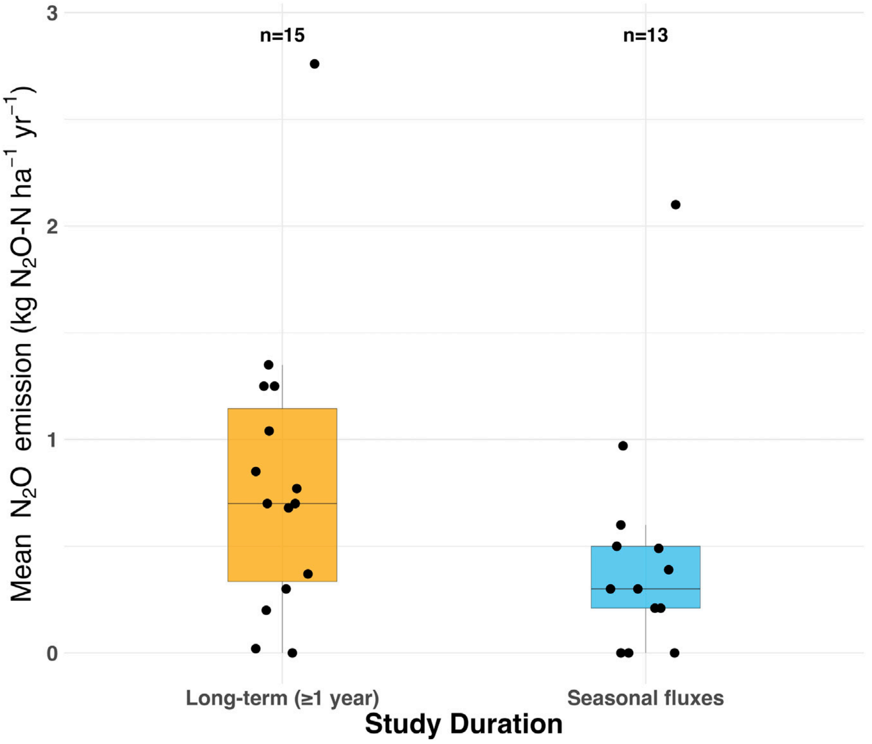

FIGURE 3
The box and whiskers represent the effect of study duration on reported mean N_2O emissions (kg N_2O-N ha-1 yr-1) from maize crop. Emission data are grouped by study duration: Long term (equal to or more than 1 year) and seasonal fluxes (a combination of short duration studies and seasonal studies-covering main cropping season. The number of observations (n) is annotated each boxplot. Long term studies tend to report higher and more variable emissions, likely capturing additional off-season pulses and episodic events missed by shorter studies.

3.2 Influence of nitrogen fertilizer application rates on N_2O emissions

We analyzed emissions across five fertilizer application rate categories (Unfertilized control or (0 kg N ha^{-1}), <50 (less than 50 but more than 0), 51–100, 101–150, >150 kg N ha^{-1}), and observed a clear trend of increasing median annual N_2O emissions (median ~0.1 kg N_2O–N ha^{-1} yr^{-1}) to ≤50 kg N ha^{-1} (~0.2), 51–100 kg N ha^{-1} (~0.4), and 101–150 kg N ha^{-1} (~0.5) and mean with higher N input levels, peaking in the 101–150 kg N ha^{-1} range (~1.11 kg N_2O-N ha^{-1} yr^{-1}; EF ≈ 0.9%) (Figure 4; Supplementary Figure S1). Higher application rates (>150 kg N ha^{-1}) are sparsely represented. Interestingly, mean emissions in the >150 kg ha^{-1} group appear low (~0.59 kg N_2O-N ha^{-1} yr^{-1}) but are however based on only six data points (Supplementary Figure S1), and may reflect limited representation, site-specific dynamics, or possibly as shown in one study, the shorter length of the study (3-month period). Emissions under control conditions (no added N) averaged 0.19 kg N_2O-N ha^{-1} yr^{-1}. This baseline still shows appreciable fluxes, possibly due to N deposition, soil mineralization, or rewetting events. These trends suggest that fertilizer-induced emissions are generally proportional to application rates, and that NUEs may decline beyond 100 kg N ha^{-1}, aligning with recent discussions around optimal fertilization thresholds in SSA (Dimkpa et al., 2023; Falconnier et al., 2023).

Our findings support the notion that moderate N application (≤100 kg/ha) may strike a balance between minimizing emissions and maintaining yield gains. Atakora et al. (2019) further found diminishing agronomic efficiency beyond 100 kg N ha^{-1}, suggesting a plateau in yield response despite increased emissions. Meanwhile, our finding that emissions do not increase exponentially at high rates differs slightly from global meta-analyses which suggest nonlinear responses at very high N levels (e.g., exponential increases above crop demand thresholds). This difference may reflect the limited number of high-N (>150 N ha^{-1}) field studies available for SSA, or it may reflect different microbial processes and physicochemical properties in tropical soils. Although some SSA assessments (Shumba et al., 2023; Tully et al., 2023) report exponential increases in N_2O emissions at higher nitrogen application rates, our synthesis reveals a predominantly linear response across the observed dataset (Figure 4; Supplementary Figure S2). Both Tully et al. (2023) and Shumba et al. (2023) found that application rates around 50 kg N ha^{-1} resulted in relatively low emissions while maintaining maize productivity. Similarly, Hickman et al. (2015) demonstrated substantial yield gains under fertilizer rates ≤100 kg N ha^{-1} in Western Kenya without proportionate increases in N_2O emissions. These findings are consistent with earlier studies showing that synchronizing N inputs with crop N demand can minimize emissions while sustaining yields (McSwiney, 2005). It is important to note, however, that these relationships can vary depending on crop

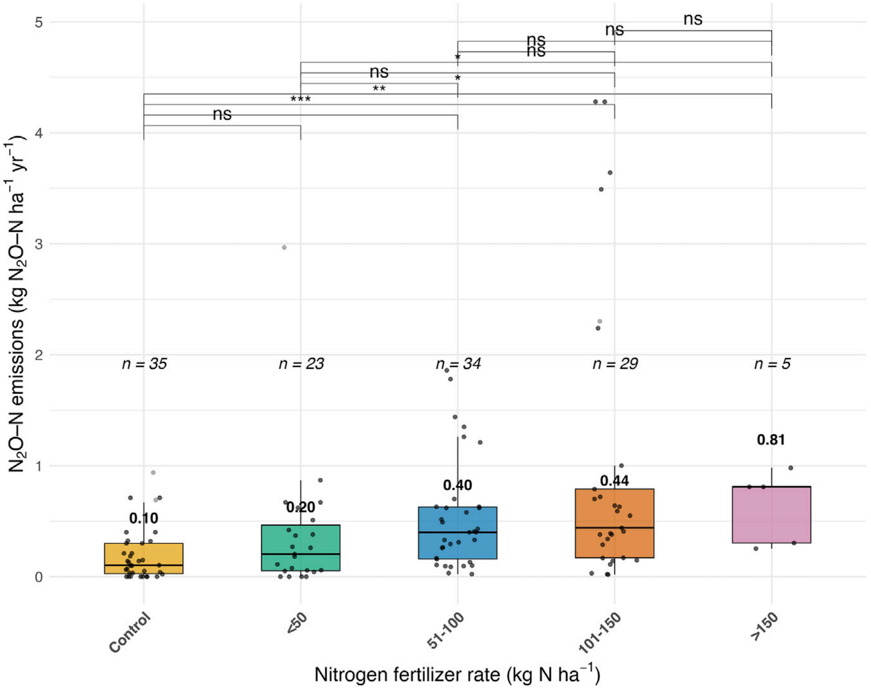

FIGURE 4
Distribution of annual N_2O emissions across nitrogen input categories. Boxplots show the median (horizontal line), interquartile range (box), and variability (whiskers), with points representing individual study observations. Sample sizes (n) for each fertilizer rate category are shown above boxplots. Grey points indicate vegetables and tea. Included studies: Brummer et al. (2008), Atakora et al. (2019), Hickman et al. (2014), Hickman et al. (2015), Kimetu et al. (2007), Macharia et al. (2021), Musafiri et al. (2020), Musafiri et al. (2021), Musuya et al. (2019), Wanyama et al. (2018), Kurgat et al. (2018), Chapuis-Lardy et al. (2009), Alasinrin et al. (2025), Roing (2004), Kimaro (2015), Zheng et al. (2019), Chikowo et al. (2007), Mapanda et al. (2011), Nyamadzawo et al. (2014).

growth stage, nitrogen uptake dynamics, and environmental conditions (Hickman et al., 2015; Maier et al., 2022).

Our second key result is the observation of high variability in emissions within each fertilizer rate category, particularly between 101 and 150 kg N ha^{-1}, emphasizing that fertilizer alone cannot fully explain N_2O fluxes. Site-level variability, likely driven by interactions among soil type, moisture, climate, and management practices modulates the emissions response. For instance, pulses of N_2O in control treatments (Barton et al., 2008; Hickman et al., 2014; Zheng et al., 2019) highlight the influence of soil organic matter turnover and rainfall dynamics, particularly during rewetting events (Davidson, 2009). Supplementary Figure S2 illustrates how the relationship between fertilizer rate and emissions varies by country, with Ghana and Nigeria showing the strongest treatment-emission signals. This supports the need for country-specific emissions factors or models, especially where climate and soil types differ. In some countries, limited or highly clustered data may obscure trends altogether, reinforcing the importance of regionalized data collection.

Due to limited availability of unfertilized control measurements in many studies, we estimate emission factors (EFs) as the ratio of total N_2O emissions to applied N fertilizer, assuming minimal contribution from soil N mining or other background sources. This approach is consistent with findings by Della Chiesa et al. (2019), who showed that although background emissions can represent a substantial proportion of cropland N_2O fluxes, fertilized treatments still emit more than background levels. The resulting EFs vary broadly, from as low as 0.05% in low-input systems up to over 4% in intensively fertilized fields, with a median around 0.4%–0.7%. Although the number of replicates is limited in several countries, most of the available studies-particularly from Kenya, Tanzania and Zimbabwe report Efs below the IPCC default of 1% (Millar et al., 2004; Chikowo et al., 2007; Chapuis-Lardy et al., 2009; Hickman et al., 2014; Rosenstock et al., 2016; Atakora et al., 2019; Musuya et al., 2019; Zheng et al., 2019; Bigaignon et al., 2020; Macharia et al., 2020; Wachiye et al., 2020; Mosongo et al., 2022; Lemarpe et al., 2023; Alasinrin et al., 2025)), suggesting that this default may overestimate typical emissions in these systems.

Our synthesis indicates that N_2O emissions generally increase with fertilizer application rate across the observed range (50–100 kg N ha^{-1}) and varies considerably by country (Supplementary Figure S2). Overall, emission factors appear lower than global default estimates, suggesting that modest fertilizer additions in SSA (50–100 kg N ha^{-1}) generally produce relatively small N_2O increases compared to similar rates elsewhere. In fact, at rates above 150 kg N ha^{-1}, some studies reported emissions equal to or even lower than those in the 101–150 kg range (Figure 4), suggesting that yield-scaled emissions may improve with higher fertilization as crop uptake offsets absolute fluxes. While data beyond 150 kg N ha^{-1} are limited in our dataset, the available evidence within the 50–150 kg N ha^{-1} range suggests reasonably predictable linear responses in most contexts, though the risk of disproportionate emission increases remains under certain soil and

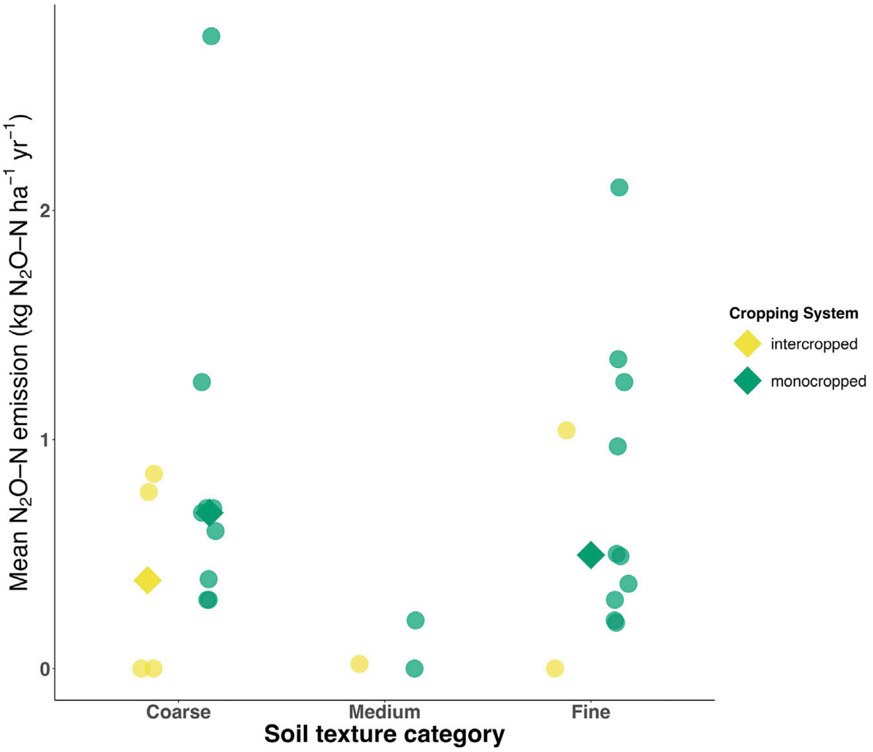

FIGURE 5
Distribution of mean nitrous oxide (N_2O) emissions from maize-based cropping systems across USDA soil texture classes (Coarse, Medium and Fine), comparing intercropped and non-intercropped systems. Diamonds indicate median values calculated separately for monocropped and intercropped systems and are shown only for soil texture categories with at least three observations per system.

climatic conditions that favor nitrification and denitrification. Taken together, our findings suggest that agricultural intensification in SSA could proceed with moderate N application rates (~50–100 kg N ha^{-1}) as a potential baseline, avoiding excessive inputs beyond crop requirements. This recommendation is based on observed trends in the reviewed studies and should be considered as guidance rather than a definitive prescription.

3.3 Crop type and soil characteristics

Although the number of available studies varies across crop types, our synthesis provides important descriptive insights into how N_2O emissions differ among key agricultural systems in SSA. These patterns, while not intended as formal statistical comparisons, help contextualize the diversity of emission dynamics in the region and identify priority systems for future measurement efforts. Across the dataset, staple crops such as maize, sorghum, and other cereals generally exhibit moderate emissions, with maize-the most extensively studied crop-ranging between 0.1 and 4.29 kg N_2O -N ha^{-1} yr^{-1}. Despite their wide cultivation, emissions in these systems are highly skewed, with median values (~0.5 kg N_2O -N ha^{-1} yr^{-1}) far below observed maxima, suggesting localized hotspots driven by site-specific management.

Sorghum and traditional cereals remain sparsely studied, though Brummer et al. (2008) reported emissions up to 1.42 g N_2O -N ha^{-1} h^{-1} for sorghum under fertilized conditions in Burkina Faso. In contrast, perennial crops such as coffee (1–1.9 kg N_2O -N ha^{-1} yr^{-1}) and tea (0.4–3.9 kg N_2O -N ha^{-1} yr^{-1}) show lower and less variable emissions. Vegetable systems, however, stand out as the most significant sources of cropland N_2O emissions in SSA, far exceeding other crop types in both intensity and variability. Emissions from these systems ranged from 0.01 to 113.4 kg N_2O -N ha^{-1} yr^{-1}, often linked to high fertilizer inputs (25–750 kg N ha^{-1}) and intensive irrigation, likely under commercial production. Similar findings have been reported across SSA (Predotova et al., 2010; Lompo et al., 2012; Masaka et al., 2014; Rosenstock et al., 2016; Kurgat et al., 2018). While vegetable production is essential for dietary diversity, frequent irrigation and heavy fertilization promote denitrification under oxygen-limited conditions, thereby amplifying N_2O losses (Qasim et al., 2021).

Beyond crop type, N_2O emissions exhibited clear but heterogeneous associations with soil texture (Figure 5). In this first order synthesis, fine-textured soils showed both higher and more variable emissions relative to coarse and medium textures, with several observations exceeding 1 kg N_2O–N ha^{-1} yr^{-1}, particularly under monocropping systems. This pattern is consistent with enhanced denitrification in clay-rich soils under conditions of elevated water-filled pore space (WFPS) and restricted oxygen diffusion (Pelster et al., 2012; Zhu et al., 2020; Hickman et al., 2021). Medium-textured soils, such as loams, exhibited consistently low emissions across cropping systems with minimal variability suggesting a potentially greater capacity to buffer moisture and nitrogen dynamics. Coarse-textured soils (e.g., Lixisols, Inceptisols)

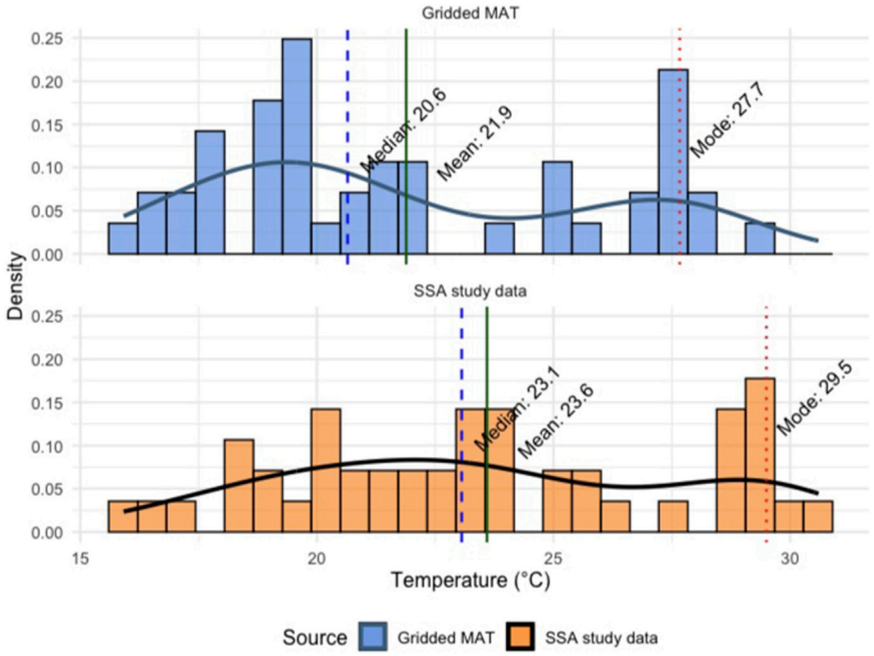

FIGURE 6
Distribution of mean annual temperature (MAT) from gridded datasets (WorldClim, upper panel) and observed field temperatures extracted directly from reviewed field studies from Sub-Saharan Africa (SSA, lower panel). Density curves reveal multimodal patterns in MAT. Vertical lines mark the mode (red dotted), mean (blue dashed), and median (continuous green), highlighting skew and asymmetry in temperature distributions relevant for nitrous oxide emission modeling. Mode represents peak of density curve (not histogram).

generally showed low to moderate emissions, although variability was evident, including relatively higher emissions under monocropping in some cases.

These patterns align with mechanistic understanding whereby coarse soils tend to be carbon-and water-limited, while fine textured soils may become nitrogen- and oxygen-limited under saturation (Pelster et al., 2012). Although data availability remains uneven across soil texture classes, these results highlight the importance of soil physical properties in shaping N_2O emission patterns in SSA and provide a useful basis for future targeted measurements and model development in SSA.

3.4 Climatic representativeness of existing studies for the SSA region

To evaluate the representativeness of study sites to the SSA region, we analyzed the distribution of temperature (Mean Annual Temperature; MAT) and rainfall (Mean Annual Precipitation; MAP) from the reviewed studies against regional climatic averages. We compared the distribution of MAT across two datasets: one representing the entire SSA region (WorldClim gridded dataset) and another specific to the study locations (Figure 6). This comparison helps contextualize the findings and assess their generalizability across the diverse environmental conditions in SSA. The pathways of N_2O production vary significantly across different climatic zones due to differences in temperature and precipitation.

MAT from gridded datasets exhibits a bimodal distribution, with a dominant mode at 19.4 °C and a secondary peak near 27 °C–28 °C (Figure 6, top panel), indicating a predominance of cooler highland or subtropical sites and fewer hotter lowland or semi-arid locations. Field reported MAT is also bimodal, but with notable differences (Figure 6, bottom panel). The dominant mode is higher, at 22.1 °C, and the second peak (~28 °C–29 °C) is less prominent than in the MAT data. The observed distribution appears shifted toward warmer temperatures, and the mean and median values are slightly higher than those of the gridded data. Despite overall agreement in the primary temperature range (≈21 °C–23 °C), both datasets underrepresent sites with MAT >25 °C, highlighting a spatial bias toward moderate-temperature regions, where studies are concentrated despite evidence of higher N_2O emissions in warmer environments (Rochette et al., 2016).

During the growing season, high-intensity rainfall often leads to increased emissions by creating anaerobic conditions that enhance denitrification. Conversely, extended dry periods suppress emissions by limiting microbial activity and reducing substrate availability but conversely increase emission pulses as the substrate becomes available to microbes in a rewetting flush (Leitner et al., 2017). To evaluate how well field studies represent actual growing season rainfall patterns across SSA, we compared mean rainfall values from 16 study locations (Annex 5) for which we could geolocate sites to the NAME_2 or NAME_3 administrative level, using CHIRPS gridded estimates (~5 km resolution). We extracted CHIRPS rainfall estimates specifically for the growing season months between 2000 and 2020, relevant to each study location. Our comparison revealed a consistent pattern: field-reported rainfall values were generally higher than corresponding gridded data for each location, with some sites showing differences of several

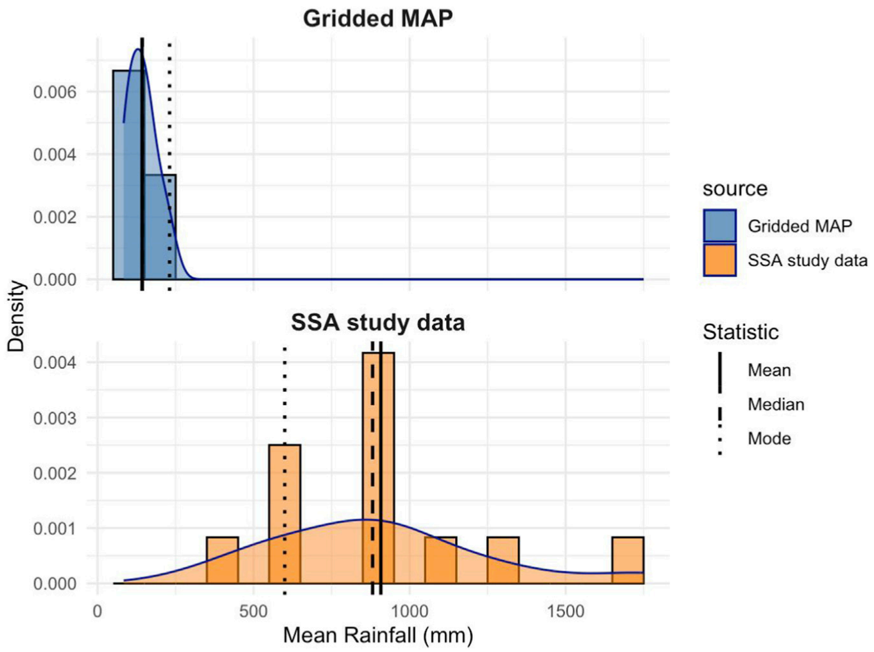

FIGURE 7
Comparison of mean growing season rainfall (mm) between gridded data (top panel) and field studies (bottom panel) for Sub-Saharan Africa (SSA) study sites. Field values represent mean rainfall reported directly in the studies reviewed. Gridded estimates were extracted from CHIRPS-high-resolution (~0.05°). Gridded rainfall was spatially matched to the study site coordinates and filtered by the relevant growing season for each location to better reflect actual crop-relevant conditions. Vertical lines represent the mean (solid), median (dashed), and mode (dotted) values within each dataset.

hundred millimeters (Figure 7). This is consistent with previous studies showing that point measurements capture localized, high-intensity convective events that gridded satellite products tend to smooth out (Dinku et al., 2010; Maidment et al., 2017; Sun et al., 2018). In addition, discrepancies may arise from reporting practices: field studies often report rainfall for the exact experimental period, whereas gridded datasets reflect standardized seasonal totals.

It is also possible that gridded data may underestimate site-specific rainfall availability particularly during extreme climate years (e.g., drought in 2022-2023 or El Nino driven excess rainfall in 2024–2025). These mismatches are critical for N_2O emissions research, as rainfall governs soil moisture dynamics and associated nitrification and denitrification processes. Furthermore, studies suggest that increasing rainfall variability under climate change may further reduce the representativeness of gridded products (Kotir, 2011; Waha et al., 2013). These discrepancies reflect spatial averaging in satellite-derived data versus localized microclimatic conditions captured by field observations, underscoring the importance of integrating site-level measurements into N_2O emission modeling frameworks.

Rainfall trends were assessed at 14 study sites with ≥20 years of data (Annex 6) to evaluate climate-driven changes in precipitation. Most sites showed increasing growing season rainfall over the past 2 decades, with more than half indicating rising trends at the 5% and 1% significance levels ($p < 0.05$; Supplementary Figure S3). This shift toward wetter conditions could boost agricultural productivity but also increases the possibility of higher N_2O emissions due to elevated soil moisture, increasing denitrification potential and/or increasing leaching of N from soils followed by downstream environmental impacts (Omotoso and Omotayo, 2024). For example, the Dano station in Burkina Faso exhibited a significant positive slope of approximately +1.5 mm/year, translating to a 30 mm increase in annual rainfall over two decades-sufficient to trigger N_2O pulses under saturated soil conditions. Conversely, only two sites, South Africa's Ehlanzeni and Zimbabwe's Chitungwiza, reported decreasing rainfall trends, indicating specific climate concerns.

4 Future research directions

4.1 Guidelines for data collection and data and metadata reporting to enhance data usability

Despite limited studies in data-poor regions, many demonstrate strong documentation and methodological transparency, including chamber details, calibration procedures, and flux calculation equations, enhancing data usability. A key strength of these studies is their grounding in local contexts and collaboration with African research institutions such as IITA (International Institute of Tropical Agriculture), CIMMYT (International Maize and Wheat Improvement Center), ILRI (International Livestock Research Institute) and national systems, reflecting a commitment to capacity building and long-term research infrastructure in SSA (Merbold et al., 2021). Many studies report spatial coordinates and climate variables—especially rainfall and temperature—critical for interpreting N_2O emissions given biases in gridded datasets, highlighting the value of initiatives like Tahmo (2025).

Key gaps remain. Many studies omit important drivers such as soil moisture, micrometeorological data, soil texture, organic matter, and microbial activity (Davidson and Kanter, 2014). Soil moisture, in particular, is rarely directly measured and is often only inferred from seasonal rainfall patterns, through statistical correlations with N_2O emissions or reported as water-filled pore space (WFPS) in a limited number of studies. For example, WFPS values reported ranged from 5% to 10% (Tully et al., 2023) to over 70% (Baggs et al., 2006), illustrating site-to-site variation and the limited availability of continuous measurements. Fertilizer management details-type, timing, and application-are often missing, limiting cross-study comparisons and assessment of fertilizer-induced emissions (Shcherbak et al., 2014).

Standardized protocols for chamber measurements, soil properties, and detailed fertilizer reporting (Butterbach-Bahl et al., 2016; de Klein et al., 2020), inclusion of zero-N plots, yield-and input-scaled metrics, and long-term data sharing through FAIR (Findable, Accessible, Interoperable, Reusable)-compliant repositories and proper metadata documentation (Fluxnet, 2025) would improve data quality and comparability.

Kenya has led N_2O research in SSA, with studies in 16 of 19 years (2000–2018) covering diverse maize systems and following rigorous protocols, providing a strong basis for model calibration. Hotter regions (MAT >25 °C), such as the Sahel, northeastern Kenya, eastern Ethiopia, and Sudan, remain underrepresented, risking underestimation of emissions. Future work should target these zones to capture SSA's full climatic diversity.

4.2 Suggestions on strengthening research of mitigation practices: reporting strengths and gaps

Beyond quantifying N_2O emissions, several studies tested mitigation practices relevant to local farming, including fertilizer rate variations, organic amendments, integrated soil fertility management, and residue and tillage management. Tillage consistently increased N_2O emissions, with conventional and minimum tillage showing higher fluxes than no-tillage (Baggs et al., 2006; Vilakazi et al., 2021; Alasinrin et al., 2025). Maize stover addition, while not improving yields, also elevated emissions, illustrating trade-offs in organic residue management (Zheng et al., 2019).

Integrated soil fertility management combining organic and mineral inputs showed that rainfall timing and soil moisture strongly influence N_2O emissions (Kimetu et al., 2007; Githongo et al., 2022). Despite these contributions, key gaps include: (1) reliance on seasonal totals or small-plot studies, (2) limited on-farm testing-only a few, like Wanyama et al. (2018), incorporate on-farm or participatory testing, and (3) few measurements of underlying mechanisms such as mineral N pools, isotopic data or microbial activity.

4.3 Future research priorities

In this section, we bring together the findings of this study to outline future research priorities for the SSA region.

4.3.1 Research priority 1: improving model representation through better input data quality for SSA

Global process-based models such as DeNitrification DeComposition (DNDC) are increasingly used to estimate N_2O emissions (Gaillard et al., 2018) but accurate simulations are limited by sparse, site-specific calibration data and the complexity of smallholder farming systems in SSA. Studies in Kenya show that DNDC simulates annual emissions and yields well but underestimates daily fluxes and short-term emission events, with systematic biases in soil moisture, temperature, and crop growth (Macharia et al., 2021; Musafiri et al., 2021). Closer integration of field experiments and modeling is needed to improve local calibration and policy relevance. Future models should better represent SSA-specific drivers, including dry–wet cycles, organic amendments, intercropping, shifting cultivation, and soil heterogeneity. Data-model integration platforms, open high-frequency time-series data, and standardized data-sharing protocols are critical for improving predictive capacity and informing sustainable fertilizer policies.

4.3.2 Research priority 2: expanding N_2O observations and multifactorial experiments in SSA

Reducing bias in EF estimates requires expanding N_2O measurements to encompass diverse cropping systems and management intensities across SSA, particularly in underrepresented systems where these are crucial for nutrition, and horticultural systems in humid and semi-humid regions. Most experiments in SSA have primarily examined the impact of single variables such as fertilizer rate or seasonal/application timing. However, future work must move toward multifactorial designs that test interactions between climate factors (e.g., warming, drought, extreme rainfall) and management practices (e.g., irrigation, organic amendments, tillage). While studies as Chikowo et al. (2007), Ntinyari et al. (2023), and Tully et al. (2023) offer valuable insights, integrated assesments of combined environmental and agronomic effects remain scarce.

Microbial processes are central to N_2O production (Schreiber et al., 2012; Butterbach-Bahl et al., 2013), yet microbial data remain largely absent in SSA field research, limiting mechanistic understanding of emissions. Integrating isotopic, functional gene, and molecular approaches analysis (e.g., qPCR, metagenomics, and stable isotope probing) would greatly improve insight into N cycling pathways (Gallarotti et al., 2021). Scarce incubation and laboratory studies further limit the ability to validate field observations. Future research should adopt systems-level approaches linking emissions to nitrogen balances, NUE (nitrogen use efficiency), socio-economic tradeoffs, productivity, profitability, and resilience outcomes to enhance policy-relevance.

4.3.3 Research priority 3: observation of legacy effects, control plot emissions and fallow period measurements

Improving EF accuracy in SSA requires accounting for legacy effects, control plot emissions, and fallow dynamics, as unfertilized plots can emit substantial N_2O due to residual soil nitrogen and organic matter mineralization, sometimes exceeding fertilized treatments (Mapanda et al., 2011; Hickman et al., 2014;

Nyamadzawo et al., 2014; Atakora et al., 2019). Vanlauwe et al. (2020); highlight the importance of accounting for background fertility in smallholder N_2O dynamics, while Della Chiesa et al. (2019) show that background emissions can comprise a significant portion of cropland fluxes. Global modeling indicates that past fertilization affects emissions beyond the active crop season (Qian et al., 2025), and fallow-period emissions, often unmonitored, can substantially contribute to cumulative N_2O losses.

Fallow and off-season emissions, driven mainly by soil organic matter mineralization after rewetting, are critical for accurate annual N_2O accounting (Cardinael et al., 2024; Shang et al., 2024). About 28% of the studies we reviewed indicate that non-cropping periods can contribute significantly, often between 10% and 20% to annual N_2O emissions, primarily due to mineralization and rainfall-induced pulses. Post-harvest and off-season emissions in Mali, Ghana, and Zimbabwe demonstrate that rainfall-driven rewetting can trigger significant N_2O pulses, even without fertilization, highlighting overlooked contributions (Ortiz-Gonzalo et al., 2018; Shumba et al., 2023; Zheng et al., 2023). Soil texture strongly shapes these dynamics: fine-textured soils retain moisture, sustaining denitrification and episodic N_2O pulses, whereas coarse soils drain quickly but can produce short-lived peaks after rainfall. Limited year-round measurements suggest dry-season and post-drought rewetting emissions are non-negligible, yet remain poorly characterized across SSA soils, highlighting a critical knowledge gap for accurate emission factor estimates.

4.3.4 Research priority 4: assessing spatial suitability and effectiveness of mitigation practices in SSA

Evidence from global meta-analyses and field trials suggests that the effectiveness of N_2O mitigation practices varies greatly across agroecological zones, soil types, and farming systems (Grados et al., 2022). Fertilizer management strategies such as optimized timing, reduced rates, and use of stabilized or slow-release fertilizers can lower emissions, but outcomes are highly context dependent. Advanced tools like N_2O stable isotope site preference analysis can help identify emission pathways and evaluate mitigation effectiveness (Yu et al., 2020). Adoption of mitigation practices ultimately depends on socioeconomic feasibility, including labor availability, profitability, access to inputs, and policy support for smallholder farmers (Steenwerth et al., 2014).

Despite strong biophysical mitigation potential, adoption of N_2O-reducing practices in SSA remains low due to socioeconomic bottlenecks such as inconsistent policies, financial constraints, lack of training and support and limited access to alternative fertilizers (Aghabeygi et al., 2024; Finizola e Silva et al., 2024; Pedersen et al., 2024). Agricultural extension and advisory services play a major role in enhancing farmer adaptation, resilience, implementation of drought tolerant or improved varieties, and agricultural management practices (Ouédraogo et al., 2019; Abegunde et al., 2020; Oyawole et al., 2020; Zakaria et al., 2020; Finizola e Silva et al., 2024). A key research priority is to generate empirical evidence on N_2O emissions under agroecological practices which are widely promoted for sustainability but remain poorly evaluated as climate mitigation strategies.

5 Conclusion

As Sub-Saharan Africa moves toward more climate-resilient and sustainable food systems, understanding the interactions between management practices, environmental conditions, and N_2O emissions is crucial. While research on N_2O emissions has increased in recent decades, it remains highly uneven across SSA. This spatial bias limits our ability to develop regionally nuanced emission factors and mitigation strategies. Across the reviewed studies, N_2O emissions were found to vary widely, reflecting the complex interplay of multiple factors. Although some categories had limited replication, nitrogen input rates, crop types, climate conditions, and measurement duration contributed to this variability. Estimated emission factors (EFs) across croplands were generally lower than the IPCC's 1% default value. Even when calculated conservatively given the scarcity of unfertilized controls, most reported EFs fall below 1%, with median values around 0.4%–0.7%. While some intensively fertilized systems exceed 2%–4%, low-input smallholder systems consistently showed values near zero. Moreover, methodological inconsistencies including differences in sampling frequency, fertilizer rates, and reporting units combined with the limited availability of long-term, year-round N_2O flux data, restrict cross-study comparability in SSA. Research efforts should prioritize high-frequency flux measurements, better integration of micrometeorological and soil biogeochemical data, and standardized reporting of agricultural practices. There is also an emerging need to investigate the role of agroecological approaches and climate-smart practices in reducing emissions. Future studies should explore these pathways while leveraging new tools like isotopic measurements, remote sensing, and process-based modeling to quantify and mitigate fertilizer-induced emissions. This synthesis provides a foundation for advancing both scientific understanding and practical efforts to manage N_2O emissions in SSA agriculture, aligning productivity goals with climate commitments.

Author contributions

TO: Methodology, Data curation, Conceptualization, Writing – original draft, Writing – review and editing. MB: Writing – original draft, Conceptualization. PA: Writing – review and editing, Data curation. MT: Writing – review and editing. GZ: Writing – original draft, Methodology, Writing – review and editing. HG: Methodology, Writing – review and editing, Writing – original draft. SL: Writing – review and editing, Supervision. CO: Writing – review and editing. WN: Writing – review and editing, Methodology. KO: Writing – review and editing. AO: Writing – review and editing, Supervision. RN: Supervision, Writing – review and editing. GO: Writing – review and editing. JS: Funding acquisition, Writing – review and editing, Supervision. EH: Supervision, Conceptualization, Writing – review and editing, Funding acquisition, Writing – original draft.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abegunde, V. O., Sibanda, M., and Obi, A. (2020). Determinants of the adoption of climate-smart agricultural practices by small-scale farming households in king cetshwayo district municipality, South Africa. *Sustainability* 12 (1), 195. doi:10.3390/su12010195

African Union (2006). "Abuja declaration on fertilizer for the african green revolution," in *declaration of the african union special summit of the heads of state and government* (Abuja: African Union).

Aghabeygi, M., Strauss, V., Paul, C., and Helming, K. (2024). Barriers of adopting sustainable soil management practices for organic and conventional farming systems. *Discov. Soil* 1 (1), 11. doi:10.1007/s44378-024-00008-1

Alasinrin, S. Y., Salako, F., Busari, M., Sainju, U., Badmus, B., and Isimikalu, T. (2025). Greenhouse gas emissions in response to tillage, nitrogen fertilization, and manure application in the tropics. *Soil Tillage Res.* 245, 106296. doi:10.1016/j.still.2024.106296

Atakora, W. K., Kwakye, P. K., Weymann, D., and Brüggemann, N. (2019). Stimulus of nitrogen fertilizers and soil characteristics on maize yield and nitrous oxide emission from ferric luvisol in the Guinea savanna agro-ecological zone of Ghana. *Sci. Afr.* 6, e00141. doi:10.1016/j.sciaf.2019.e00141

Baggs, E. M., Chebii, J., and Ndufa, J. K. (2006). A short-term investigation of trace gas emissions following tillage and no-tillage of agroforestry residues in Western Kenya. *Soil Tillage Res.* 90 (1), 69–76. doi:10.1016/j.still.2005.08.006

Barton, L., Kiese, R., Gatter, D., Butterbach-Bahl, K., Buck, R., Hinz, C., et al. (2008). Nitrous oxide emissions from a cropped soil in a semi-arid climate. *Glob. Change Biol.* 14 (1), 177–192. doi:10.1111/j.1365-2486.2007.01474.x

Bigaignon, L., Delon, C., Ndiaye, O., Galy-Lacaux, C., Serça, D., Guérin, F., et al. (2020). Understanding N2O emissions in African ecosystems: assessments from a semi-arid savanna grassland in Senegal and sub-tropical agricultural fields in Kenya. *Sustainability* 12 (21), 8875. doi:10.3390/su12218875

Bodirsky, B. L., Popp, A., Lotze-Campen, H., Dietrich, J. P., Rolinski, S., Weindl, I., et al. (2014). Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nat. Commun.* 5 (1), 3858. doi:10.1038/ncomms4858

Brümmer, C., Brüggemann, N., Butterbach-Bahl, K., Falk, U., Szarzynski, J., Vielhauer, K., et al. (2008). Soil-atmosphere exchange of N2O and NO in near-natural savanna and agricultural land in Burkina Faso (W. Africa). *Ecosystems* 11 (4), 582–600. doi:10.1007/s10021-008-9144-1

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., and Zechmeister-Boltenstern, S. (2013). Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Philosophical Trans. R. Soc. B Biol. Sci.* 368 (1621), 20130122. doi:10.1098/rstb.2013.0122

Butterbach-Bahl, K., Sander, B. O., Pelster, D., and Díaz-Pinés, E. (2016). "Quantifying greenhouse gas emissions from managed and natural soils," in *Methods for measuring greenhouse gas balances and evaluating mitigation options in smallholder agriculture.* Editor T. S. Rosenstock (Cham: Springer International Publishing), 71–96. doi:10.1007/978-3-319-29794-1_4

Cardinael, R., Barton, L., Corbeels, M., Six, J., Rowlings, D., Shumba, A., et al. (2024). Soil N_2O emissions during dry fallow periods. *Glob. Change Biol.* 30 (7), e17403. doi:10.1111/gcb.17403

Chapuis-Lardy, L., Metay, A., Martinet, M., Rabenarivo, M., Toucet, J., Douzet, J., et al. (2009). Nitrous oxide fluxes from Malagasy agricultural soils. *Geoderma* 148 (3–4), 421–427. doi:10.1016/j.geoderma.2008.11.015

Chikowo, R., Mapfumo, P., Leffelaar, P. A., and Giller, K. E. (2007). Integrating legumes to improve N cycling on smallholder farms in sub-humid Zimbabwe: resource quality, biophysical and environmental limitations. *Nutrient Cycl. Agroecosyst.* 76 (2–3), 219–231. doi:10.1007/s10705-005-2651-y

Cui, X., Bo, Y., Adalibieke, W., Winiwarter, W., Zhang, X., Davidson, E. A., et al. (2024). The global potential for mitigating nitrous oxide emissions from croplands. *One Earth* 7 (3), 401–420. doi:10.1016/j.oneear.2024.01.005

Davidson, E. A. (2009). The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nat. Geosci.* 2 (9), 659–662. doi:10.1038/ngeo608

Davidson, E., and Kanter, D. (2014). Inventories and scenarios of nitrous oxide emissions. *Environ. Res. Lett.* 9, 105012. doi:10.1088/1748-9326/9/10/105012

de Klein, C. A. M., Harvey, M. J., Clough, T. J., Petersen, S. O., Chadwick, D. R., and Venterea, R. T. (2020). Global research alliance N2O chamber methodology guidelines: introduction, with health and safety considerations. *J. Environ. Qual.* 49 (5), 1073–1080. doi:10.1002/jeq2.20131

Della Chiesa, T., Piñeiro, G., and Yahdjian, L. (2019). Gross, background, and net anthropogenic soil nitrous oxide emissions from soybean, corn, and wheat croplands. *J. Environ. Qual.* 48 (1), 16–23. doi:10.2134/jeq2018.07.0262

Dimkpa, C., Adzawla, W., Pandey, R., Atakora, W. K., Kouame, A. K., Jemo, M., et al. (2023). Fertilizers for food and nutrition security in Sub-Saharan Africa: an overview of soil health implications. *Front. Soil Sci.* 3, 1123931. doi:10.3389/fsoil.2023.1123931

Dinku, T., Connor, S., and Ceccato, P. (2010). "Comparison of CMORPH and TRMM-3B42 over mountainous regions of Africa and South America," in *Satellite rainfall applications for surface hydrology*, 193–204. doi:10.1007/978-90-481-2915-7_11

Elrys, A. S., Metwally, M. S., Raza, S., Alnaimy, M. A., Shaheen, S. M., Chen, Z., et al. (2020). How much nitrogen does Africa need to feed itself by 2050? *J. Environ. Manag.* 268, 110488. doi:10.1016/j.jenvman.2020.110488

Falconnier, G. N., Cardinael, R., Corbeels, M., Baudron, F., Chivenge, P., Couëdel, A., et al. (2023). The input reduction principle of agroecology is wrong when it comes to mineral fertilizer use in Sub-Saharan Africa. *Outlook Agric.* 52 (3), 311–326. doi:10.1177/00307270231199795

Fick, S. E., and Hijmans, R. J. (2017). WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* 37 (12), 4302–4315. doi:10.1002/joc.5086

Finizola e Silva, M., Van Schoubroeck, S., Cools, J., and Van Passel, S. (2024). A systematic review identifying the drivers and barriers to the adoption of climate-smart agriculture by smallholder farmers in Africa. *Front. Environ. Econ.* 3, 1356335. doi:10.3389/frevc.2024.1356335

Fluxnet (2025). Fluxnet. Available online at: https://fluxnet.org/(Accessed September 12, 2025).

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., et al. (2015). The climate hazards infrared precipitation with Stations—a new environmental record for monitoring extremes. *Sci. Data* 2 (1), 150066. doi:10.1038/sdata.2015.66

Gaillard, R. K., Jones, C. D., Ingraham, P., Collier, S., Izaurralde, R. C., Jokela, W., et al. (2018). Underestimation of N2O emissions in a comparison of the DayCent, DNDC, and EPIC models. *Ecol. Appl.* 28 (3), 694–708. doi:10.1002/eap.1674

Gallarotti, N., Barthel, M., Verhoeven, E., Pereira, E. I. P., Bauters, M., Baumgartner, S., et al. (2021). In-depth analysis of N2O fluxes in tropical forest soils of the Congo Basin combining isotope and functional gene analysis. *ISME J.* 15 (11), 3357–3374. doi:10.1038/s41396-021-01004-x

Githongo, M. W., Musafiri, C. M., Macharia, J. M., Kiboi, M. N., Fliessbach, A., Muriuki, A., et al. (2022). Greenhouse gas fluxes from selected soil fertility management practices in humic nitisols of upper eastern Kenya. *Sustainability* 14 (3), 1938. doi:10.3390/su14031938

Grados, D., Butterbach-Bahl, K., Chen, J., Jan van Groenigen, K., Olesen, J. E., Willem van Groenigen, J., et al. (2022). Synthesizing the evidence of nitrous oxide mitigation practices in agroecosystems. *Environ. Res. Lett.* 17 (11), 114024. doi:10.1088/1748-9326/ac9b50

Hickman, J. E., Palm, C. A., Mutuo, P., Melillo, J. M., and Tang, J. (2014). Nitrous oxide (N2O) emissions in response to increasing fertilizer addition in maize (zea mays L.) agriculture in western Kenya. *Nutrient Cycl. Agroecosyst.* 100 (2), 177–187. doi:10.1007/s10705-014-9636-7

Hickman, J. E., Tully, K. L., Groffman, P. M., Diru, W., and Palm, C. A. (2015). A potential tipping point in tropical agriculture: avoiding rapid increases in nitrous oxide fluxes from agricultural intensification in Kenya: non-linear N $_2$ O in tropical agriculture. *J. Geophys. Res. Biogeosciences* 120 (5), 938–951. doi:10.1002/2015JG002913

Hickman, J. E., Kaya, B., Kebede, A., Kandji, S., Fitch, L., Neill, C., et al. (2021). Little effect of land use on N $_2$ O and NO emission pulses following rewetting of dry soils across seasonally dry sub-Saharan Africa. *J. Geophys. Res. Biogeosciences* 126 (1), e2020JG005742. doi:10.1029/2020JG005742

Intergovernmental Panel On Climate Change (Ipcc) (2023). *Climate change 2021 – the physical science basis: Working group I contribution to the sixth assessment report of the intergovernmental panel on climate change*. 1st edn. Cambridge University Press. doi:10.1017/9781009157896

IPCC (2006a). 2006 IPCC guidelines for national greenhouse gas inventories. 5.1-5.54. Available online at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_05_Ch5_Cropland.pdf.

IPCC (2006b). N$_2$O emissions from managed soils, and Co$_2$ emissions from lime and urea application. Available online at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf.

Jayne, T. S., and Sanchez, P. A. (2021). Agricultural productivity must improve in Sub-Saharan Africa. *Science* 372 (6546), 1045–1047. doi:10.1126/science.abf5413

Kim, D.-G., Grieco, E., Bombelli, A., Hickman, J. E., and Sanz-Cobena, A. (2021). Challenges and opportunities for enhancing food security and greenhouse gas mitigation in smallholder farming in Sub-Saharan Africa. A review. *Food Secur.* 13 (2), 457–476. doi:10.1007/s12571-021-01149-9

Kimaro, A. A., Mpanda, M., Rioux, J., Aynekulu, E., Shaba, S., Thiong'o, M., et al. (2015). Is conservation agriculture 'climate-smart' for maize farmers in the highlands of Tanzania?. *Nutr. Cycl. Agroecosystems*, 1–12. doi:10.1007/s10705-015-9711-8

Kimetu, J. M., Mugendi, D. N., Bationo, A., Palm, C. A., Mutuo, P. K., Kihara, J., et al. (2007). Partial balance of nitrogen in a maize cropping system in humic nitisol of central Kenya. *Nutrient Cycl. Agroecosyst.* 76 (2–3), 261–270. doi:10.1007/s10705-005-6082-6

Kotir, J. H. (2011). Climate change and variability in Sub-Saharan Africa: a review of current and future trends and impacts on agriculture and food security. *Environ. Dev. Sustain.* 13 (3), 587–605. doi:10.1007/s10668-010-9278-0

Koussoubé, E., and Nauges, C. (2016). Returns to fertiliser use: does it pay enough? Some new evidence from Sub-Saharan Africa. *Eur. Rev. Agric. Econ.*, jbw018v1. doi:10.1093/erae/jbw018

Kurgat, B. K., Stöber, S., Mwonga, S., Lotze-Campen, H., and Rosenstock, T. S. (2018). Livelihood and climate trade-offs in Kenyan peri-urban vegetable production. *Agric. Syst.* 160, 79–86. doi:10.1016/j.agsy.2017.10.003

Leitner, S., Homyak, P. M., Blankinship, J. C., Eberwein, J., Jenerette, G. D., Zechmeister-Boltenstern, S., et al. (2017). Linking NO and N2O emission pulses with the mobilization of mineral and organic N upon rewetting dry soils. *Soil Biol. Biochem.* 115, 461–466. doi:10.1016/j.soilbio.2017.09.005

Leitner, S., Pelster, D. E., Werner, C., Merbold, L., Baggs, E. M., Mapanda, F., et al. (2020). Closing maize yield gaps in Sub-Saharan Africa will boost soil N2O emissions. *Curr. Opin. Environ. Sustain.* 47, 95–105. doi:10.1016/j.cosust.2020.08.018

Lemarpe, S. E., Musafiri, C. M., Kiboi, M. N., Ng'etich, O. K., Macharia, J. M., Shisanya, C. A., et al. (2023). Smallholder cropping systems contribute limited greenhouse gas fluxes in upper eastern Kenya. *Nature-Based Solutions* 4, 100098. doi:10.1016/j.nbsj.2023.100098

Lompo, D. J., Sangaré, S. A. K., Compaoré, E., Papoada Sedogo, M., Predotova, M., Schlecht, E., et al. (2012). Gaseous emissions of nitrogen and carbon from urban vegetable gardens in bobo-dioulasso, Burkina Faso. *J. Plant Nutr. Soil Sci.* 175 (6), 846–853. doi:10.1002/jpln.201200012

Macharia, J. M., Pelster, D. E., Ngetich, F. K., Shisanya, C. A., Mucheru-Muna, M., and Mugendi, D. N. (2020). Soil greenhouse gas fluxes from maize production under different soil fertility management practices in East Africa. *J. Geophys. Res. Biogeosciences* 125 (7), e2019JG005427. doi:10.1029/2019JG005427

Macharia, J. M., Ngetich, F. K., and Shisanya, C. A. (2021). Parameterization, calibration and validation of the DNDC model for carbon dioxide, nitrous oxide and maize crop performance estimation in East Africa. *Heliyon* 7 (5), e06977. doi:10.1016/j.heliyon.2021.e06977

Maidment, R. I., Grimes, D., Black, E., Tarnavsky, E., Young, M., Greatrex, H., et al. (2017). A new, long-term daily satellite-based rainfall dataset for operational monitoring in Africa. *Sci. Data* 4 (1), 170063. doi:10.1038/sdata.2017.63

Maier, R., Hörtnagl, L., and Buchmann, N. (2022). Greenhouse gas fluxes (CO2, N2O and CH4) of pea and maize during two cropping seasons: drivers, budgets, and emission factors for nitrous oxide. *Sci. Total Environ.* 849, 157541. doi:10.1016/j.scitotenv.2022.157541

Mapanda, F., Wuta, M., Nyamangara, J., and Rees, R. M. (2011). Effects of organic and mineral fertilizer nitrogen on greenhouse gas emissions and plant-captured carbon under maize cropping in Zimbabwe. *Plant Soil* 343 (1–2), 67–81. doi:10.1007/s11104-011-0753-7

Masaka, J., Nyamangara, J., and Wuta, M. (2014). Nitrous oxide emissions from wetland soil amended with inorganic and organic fertilizers. *Archives Agron. Soil Sci.* 60 (10), 1363–1387. doi:10.1080/03650340.2014.890707

Masso, C., Baijukya, F., Ebanyat, P., Bouaziz, S., Wendt, J., Bekunda, M., et al. (2017). Dilemma of nitrogen management for future food security in Sub-Saharan Africa – a review. *Soil Res.* 55 (6), 425–434. doi:10.1071/SR16332

McGuire, S. (2015). 'FAO, IFAD, and WFP. The state of food insecurity in the world 2015: meeting the 2015 international hunger targets: taking stock of uneven progress. *Adv. Nutr. Bethesda, Md.* Rome: FAO, 6(5), pp. 623–624. doi:10.3945/an.115.009936

Merbold, L., Scholes, R. J., Acosta, M., Beck, J., Bombelli, A., Fiedler, B., et al. (2021). Opportunities for an African greenhouse gas observation system. *Reg. Environ. Change* 21 (4), 104. doi:10.1007/s10113-021-01823-w

Millar, N., Ndufa, J. K., Cadisch, G., and Baggs, E. M. (2004). Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics. *Glob. Biogeochem. Cycles* 18 (1). doi:10.1029/2003GB002114

Mosongo, P. S., Pelster, D. E., Li, X., Gaudel, G., Wang, Y., Chen, S., et al. (2022). Greenhouse gas emissions response to fertilizer application and soil moisture in dry agricultural uplands of central Kenya. *Atmosphere* 13 (3), 463. doi:10.3390/atmos13030463

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., and Foley, J. A. (2012). Closing yield gaps through nutrient and water management. *Nature* 490 (7419), 254–257. doi:10.1038/nature11420

Musafiri, C. M., Macharia, J. M., Kiboi, M. N., Ng'etich, O. K., Shisanya, C. A., Okeyo, J. M., et al. (2021). Comparison between observed and DeNitrification-DeComposition model-based nitrous oxide fluxes and maize yields under selected soil fertility management technologies in Kenya. *Plant Soil* 463 (1–2), 395–413. doi:10.1007/s11104-021-04924-x

Musuya, D., Opala, P., and Ogindo, H. (2019). *Nitrogen sources and their effects on nitrous oxide emission and maize yield in western Kenya.* 0507.

Ntinyari, W., Reichel, R., Gweyi-Onyango, J. P., Giweta, M., Wissel, H., Masso, C., et al. (2023). Nitrogen fertilization and liming increased CO $_2$ and N $_2$ O emissions from tropical ferralsols, but not from a vertisol. *Soil Use Manag.* 39 (3), 1125–1139. doi:10.1111/sum.12927

Nyamadzawo, G., Wuta, M., Nyamangara, J., Smith, J. L., and Rees, R. M. (2014). Nitrous oxide and methane emissions from cultivated seasonal wetland (dambo) soils with inorganic, organic and integrated nutrient management. *Nutrient Cycl. Agroecosyst.* 100 (2), 161–175. doi:10.1007/s10705-014-9634-9

Omotoso, A. B., and Omotayo, A. O. (2024). The interplay between agriculture, greenhouse gases, and climate change in Sub-Saharan Africa. *Reg. Environ. Change* 24 (1), 1. doi:10.1007/s10113-023-02159-3

Ortiz-Gonzalo, D., de Neergaard, A., Vaast, P., Suárez-Villanueva, V., Oelofse, M., and Rosenstock, T. S. (2018). Multi-scale measurements show limited soil greenhouse gas emissions in Kenyan smallholder coffee-dairy systems. *Sci. Total Environ.* 626, 328–339. doi:10.1016/j.scitotenv.2017.12.247

Ouédraogo, M., Houessionon, P., Zougmoré, R. B., and Partey, S. T. (2019). Uptake of climate-smart agricultural technologies and practices: actual and potential adoption rates in the climate-smart village site of Mali. *Sustainability* 11 (17), 4710. doi:10.3390/su11174710

Oyawole, F. P., Shittu, A., Kehinde, M., Ogunnaike, G., and Akinjobi, L. T. (2020). Women empowerment and adoption of climate-smart agricultural practices in Nigeria. *Afr. J. Econ. Manag. Stud.* 12 (1), 105–119. doi:10.1108/AJEMS-04-2020-0137

Pedersen, S. M., Erekalo, K. T., Christensen, T., Denver, S., Gemtou, M., Fountas, S., et al. (2024). Drivers and barriers to climate-smart agricultural practices and technologies adoption: insights from stakeholders of five European food supply chains. *Smart Agric. Technol.* 8, 100478. doi:10.1016/j.atech.2024.100478

Pelster, D. E., Chantigny, M. H., Rochette, P., Angers, D. A., Rieux, C., and Vanasse, A. (2012). Nitrous oxide emissions respond differently to mineral and organic nitrogen sources in contrasting soil types. *J. Environ. Qual.* 41 (2), 427–435. doi:10.2134/jeq2011.0261

Perez-Quezada, J. F., Meijide, A., and Leitner, S. (2023). Editorial: greenhouse gas measurements in underrepresented areas of the world. *Front. Soil Sci.* 3, 1240930. doi:10.3389/fsoil.2023.1240930

Piñeiro-Guerra, J. M., Lewczuk, N. A., Della Chiesa, T., Araujo, P. I., Acreche, M., Alvarez, C., et al. (2025). Spatial variability of nitrous oxide emissions from croplands and unmanaged natural ecosystems across a large environmental gradient. *J. Environ. Qual.* 54 (2), 483–498. doi:10.1002/jeq2.20663

Predotova, M., Gebauer, J., Diogo, R. V., Schlecht, E., and Buerkert, A. (2010). Emissions of ammonia, nitrous oxide and carbon dioxide from urban gardens in Niamey, niger. *Field Crops Res.* 115 (1), 1–8. doi:10.1016/j.fcr.2009.09.010

Qasim, W., Zhao, Y., Wan, L., Lv, H., Lin, S., Gettel, G. M., et al. (2021). The potential importance of soil denitrification as a major N loss pathway in intensive greenhouse vegetable production systems. *Plant Soil* 471, 157–174. doi:10.1007/s11104-021-05187-2

Qian, H., Yuan, Z., Chen, N., Zhu, X., Huang, S., Lu, C., et al. (2025). Legacy effects cause systematic underestimation of N2O emission factors. *Nat. Commun.* 16 (1), 2775. doi:10.1038/s41467-025-58090-0

R Core Team (2024). *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Available online at: https://www.R-project.org/.

Roing, K., Goosens, A., Diels, J., Sanginga, N., Andren, O., and Vanlauwe, B. (2004). Initial nitrous oxide fluxes from a maize-legume cropping system in a soil of the derived Savanna zone of Nigeria-effect of fertilizer and incoporated organic matter. *West Afr. J. Appl. Ecol.* 6 (1). doi:10.4314/wajae.v6i1.45620

Ravishankara, A. R., Daniel, J. S., and Portmann, R. W. (2009). Nitrous oxide (N2O): the dominant ozone-depleting substance emitted in the 21st century. *Science* 326 (5949), 123–125. doi:10.1126/science.1176985

Rosenstock, T. S., Rufino, M. C., Butterbach-Bahl, K., and Wollenberg, E. (2013). Toward a protocol for quantifying the greenhouse gas balance and identifying mitigation options in smallholder farming systems. *Environ. Res. Lett.* 8 (2), 021003. doi:10.1088/1748-9326/8/2/021003

Rosenstock, T. S., Mpanda, M., Pelster, D. E., Butterbach-Bahl, K., Rufino, M. C., Thiong'o, M., et al. (2016). Greenhouse gas fluxes from agricultural soils of Kenya and Tanzania. *J. Geophys. Res. Biogeosciences* 121 (6), 1568–1580. doi:10.1002/2016JG003341

Schreiber, F., Wunderlin, P., Udert, K. M., and Wells, G. F. (2012). Nitric oxide and nitrous oxide turnover in natural and engineered microbial communities: biological pathways, chemical reactions, and novel technologies. *Front. Microbiol.* 3, 372. doi:10.3389/fmicb.2012.00372

Shang, Z., Cui, X., van Groenigen, K. J., Kuhnert, M., Abdalla, M., Luo, J., et al. (2024). Global cropland nitrous oxide emissions in fallow period are comparable to growing-season emissions. *Glob. Change Biol.* 30 (2), e17165. doi:10.1111/gcb.17165

Shcherbak, I., Millar, N., and Robertson, G. P. (2014). Global metaanalysis of the nonlinear response of soil nitrous oxide (N2O) emissions to fertilizer nitrogen. *Proc. Natl. Acad. Sci. U. S. A.* 111 (25), 9199–9204. doi:10.1073/pnas.1322434111

Shumba, A., Chikowo, R., Corbeels, M., Six, J., Thierfelder, C., and Cardinael, R. (2023). Long-term tillage, residue management and crop rotation impacts on N2O and CH4 emissions from two contrasting soils in sub-humid Zimbabwe. *Agric. Ecosyst. and Environ.* 341, 108207. doi:10.1016/j.agee.2022.108207

Steenwerth, K. L., Hodson, A. K., Bloom, A. J., Carter, M. R., Cattaneo, A., Chartres, C. J., et al. (2014). Climate-smart agriculture global research agenda: scientific basis for action. *Agric. and Food Secur.* 3 (1), 11. doi:10.1186/2048-7010-3-11

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., and Hsu, K. (2018). A review of global precipitation data sets: data sources, estimation, and intercomparisons. *Rev. Geophys.* 56 (1), 79–107. doi:10.1002/2017RG000574

Syakila, A., and Kroeze, C. (2011). 'The global nitrous oxide budget revisited', *Greenh. Gas Meas. Manag.*, 1(1), 17–26. doi:10.3763/ghgmm.2010.0007

TAHMO (2025). TAHMO, TAHMO. Available online at: https://tahmo.org/ (Accessed September 12, 2025).

Tian, H., Yang, J., Xu, R., Lu, C., Canadell, J. G., Davidson, E. A., et al. (2019). Global soil nitrous oxide emissions since the preindustrial era estimated by an ensemble of terrestrial biosphere models: Magnitude, attribution, and uncertainty. *Glob. Change Biol.* 25 (2), 640–659. doi:10.1111/gcb.14514

Tian, X., Cong, J., Wang, H., Zheng, H., Wang, Z., Chu, Y., et al. (2023). Cropland nitrous oxide emissions exceed the emissions of RCP 2.6: a global spatial analysis. *Sci. Total Environ.* 858, 159738. doi:10.1016/j.scitotenv.2022.159738

Tian, H., Pan, N., Thompson, R. L., Canadell, J. G., Suntharalingam, P., Regnier, P., et al. (2024). Global nitrous oxide budget (1980–2020). *Earth Syst. Sci. Data* 16 (6), 2543–2604. doi:10.5194/essd-16-2543-2024

Tongwane, M. I., and Moeletsi, M. E. (2018). A review of greenhouse gas emissions from the agriculture sector in Africa. *Agric. Syst.* 166, 124–134. doi:10.1016/j.agsy.2018.08.011

Tully, K. L., Hickman, J. E., Russo, T. A., Neill, C., Matata, P., Nyadzi, G., et al. (2023). The fate of nitrogen during agricultural intensification in East Africa: nitrogen budgets in contrasting agroecosystems. *J. Geophys. Res. Biogeosciences* 128 (7), e2022JG007128. doi:10.1029/2022JG007128

Van Loon, M. P., Hijbeek, R., Ten Berge, H. F. M., De Sy, V., Ten Broeke, G. A., Solomon, D., et al. (2019). Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. *Glob. Change Biol.* 25 (11), 3720–3730. doi:10.1111/gcb.14783

Vanlauwe, B., and Dobermann, A. (2020). Sustainable intensification of agriculture in Sub-Saharan Africa: first things first. *Front. Agric. Sci. Eng.* 7, 376. doi:10.15302/J-FASE-2020351

Vanlauwe, B. A., Tilahun, A., Bationo, P. S., Bindraban, H., Breman, R., Cardinael, A., et al. (2023). Fertilizer and soil health in africa. The role of fertilizer in building soil health to sustain farming and address climate change.

Vilakazi, B. S., Zengeni, R., Mafongoya, P., Ntsasa, N., and Tshilongo, J. (2021). Seasonal effluxes of greenhouse gases under different tillage and N fertilizer management in a dryland maize mono-crop. *J. Soil Sci. Plant Nutr.* 21 (4), 2873–2883. doi:10.1007/s42729-021-00574-1

Wachiye, S., Merbold, L., Vesala, T., Rinne, J., Räsänen, M., Leitner, S., et al. (2020). Soil greenhouse gas emissions under different land-use types in savanna ecosystems of Kenya. *Biogeosciences* 17 (8), 2149–2167. doi:10.5194/bg-17-2149-2020

Waha, K., Müller, C., and Rolinski, S. (2013). Separate and combined effects of temperature and precipitation change on maize yields in Sub-Saharan Africa for mid-to late-21st century. *Glob. Planet. Change* 106, 1–12. doi:10.1016/j.gloplacha.2013.02.009

Wang, Q., Zhou, F., Shang, Z., Ciais, P., Winiwarter, W., Jackson, R. B., et al. (2020). Data-driven estimates of global nitrous oxide emissions from croplands. *Natl. Sci. Rev.* 7 (2), 441–452. doi:10.1093/nsr/nwz087

Wanyama, I., Pelster, D. E., Arias-Navarro, C., Butterbach-Bahl, K., Verchot, L. V., and Rufino, M. C. (2018). Management intensity controls soil N2O fluxes in an afromontane ecosystem. *Sci. Total Environ.* 624, 769–780. doi:10.1016/j.scitotenv.2017.12.081

World Bank (2024). World development indicators. Available online at: https://databank.worldbank.org/source/world-development-indicators (Accessed June 16, 2025).

Xu, R., Tian, H., Pan, S., Prior, S. A., Feng, Y., and Dangal, S. R. S. (2020). Global N2O emissions from cropland driven by nitrogen addition and environmental factors: Comparison and uncertainty analysis. *Glob. Biogeochem. Cycles* 34 (12), e2020GB006698. doi:10.1029/2020GB006698

Yu, L., Harris, E., Lewicka-Szczebak, D., Barthel, M., Blomberg, M. R. A., Harris, S. J., et al. (2020). What can we learn from N2O isotope data? – analytics, processes and modelling. *Rapid Commun. Mass Spectrom.* 34 (20), e8858. doi:10.1002/rcm.8858

Zakaria, A., Azumah, S. B., Appiah-Twumasi, M., and Dagunga, G. (2020). Adoption of climate-smart agricultural practices among farm households in Ghana: the role of farmer participation in training programmes. *Technol. Soc.* 63, 101338. doi:10.1016/j.techsoc.2020.101338

Zhang, T., Wu, X., Li, C., and Cheng, C. (2024). Crop-specific emission projection suggests peaking of agricultural N_2 O by the middle century. *Environ. Sci. and Technol.* 58 (52), 22967–22979. doi:10.1021/acs.est.4c06592

Zheng, J., Qu, Y., Kilasara, M. M., Mmari, W. N., and Funakawa, S. (2019). Soil-atmosphere exchange of nitrous oxide in two Tanzanian croplands: effects of nitrogen and stover management. *Agric. For. Meteorology* 275, 24–36. doi:10.1016/j.agrformet.2019.05.009

Zheng, J., Canarini, A., Fujii, K., Mmari, W. N., Kilasara, M. M., and Funakawa, S. (2023). Cropland intensification mediates the radiative balance of greenhouse gas emissions and soil carbon sequestration in maize systems of sub-Saharan Africa. *Glob. Change Biol.* 29 (6), 1514–1529. doi:10.1111/gcb.16550

Zhu, Y., Merbold, L., Leitner, S., Xia, L., Pelster, D. E., Diaz-Pines, E., et al. (2020). Influence of soil properties on N2O and CO2 emissions from excreta deposited on tropical pastures in Kenya. *Soil Biol. Biochem.* 140, 107636. doi:10.1016/j.soilbio.2019.107636