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Impact of fertilizer applications on grain and vegetable crops in smallholder Mixed Crop-Livestock (MCL) systems in West Africa

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ABSTRACT

Mixed crop-livestock (MCL) systems can enhance crop yield, and improve nutrient cycling while reducing chemical fertilizer use. However, only a limited number of studies that reported this assumption were conducted under real-world conditions of small-scale farmers or followed an integrated approach. A survey was conducted in the 2021/2022 and 2022/2023 cropping seasons in Ghana and Burkina Faso, respectively, to determine the impact of fertilizer application practices on the yield of grain and vegetable crops in real-world MCL systems. Detailed information on fertilizer management practice and yield was collected from 317 MCL system farms distributed across three (3) districts/provinces in the Upper East region of Ghana and over the Plateau central of Burkina Faso, respectively summarising data on their grain and vegetable yields under (1) major fertilizer sources; organic, chemical, and combined (organic + chemical), (2) N fertilizer rate (crop x country specific N kg ha^{-1} recommendation), (3) application timing of fertilizer sources (recommended crop x country specific time of application), and (4) fertilizer placement methods (broadcast versus side placement versus furrow). Results show that the use of different fertilizer source increased ($P < 0.05$) yields of all grain crops (in Burkina Faso) and maize, rice, sorghum, millet, cowpea and all vegetable crops (in Ghana). The application of crop and country specific recommended N rates significantly influenced ($P < 0.05$) yields of sorghum, cowpea and green beans in Burkina Faso and rice, sorghum, millet, cowpea and pepper in Ghana compared to low N application rates. The contribution of manure application and appropriate timing on yield mostly differed between countries, such that high tendencies of increased yields were recorded when manure was applied for 0–3 weeks before planting (WBP) in Burkina Faso, while in Ghana, the highest yield improvements were observed when application periods exceeded 3 WBP. Not broadcasting chemical fertilizer only increased ($P < 0.05$) yields of millet and green beans (in Burkina Faso) and vegetable crops in both countries. These results help improve our understanding of fertilizer practices in mixed crop-livestock systems of Burkina Faso and Ghana, and may help guide recommended fertilizer management in MCL systems of these countries and similar ecologies in West Africa.

1. Introduction

Mixed crop-livestock system (MCLS) represents an agricultural approach that combines crop and livestock production activities to harness advantages arising from the ensuing interplay between crops and livestock (Ryschawy et al., 2012). It is a common farming practice in

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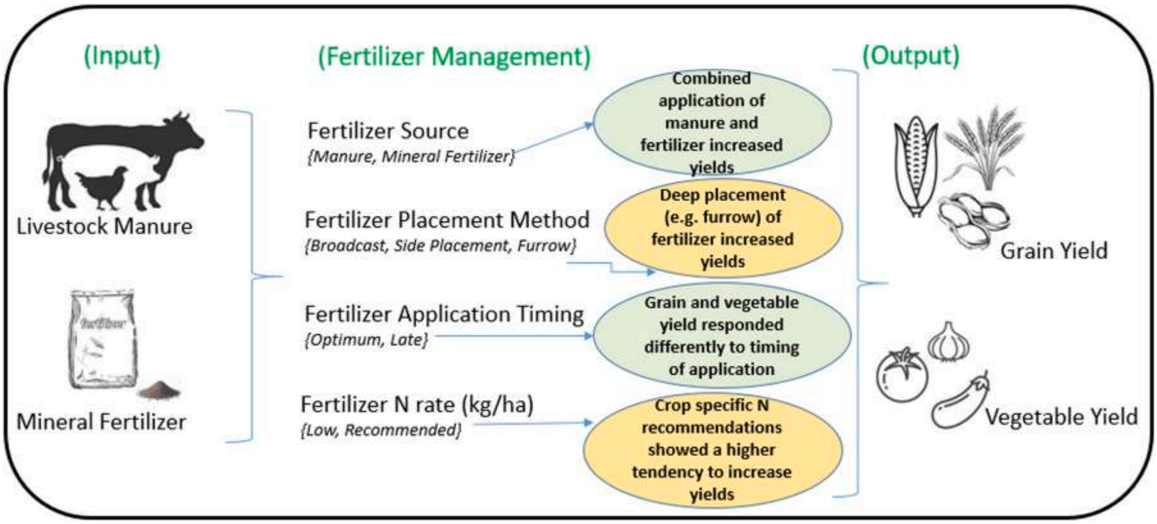

Fig. 1. An illustrative summary of the Impact of fertilizer applications on grain and vegetable crops. Graphic vector elements designed and downloaded from Freepik (https://www.freepik.com/.).

much of the Sudan savannah zones of West Africa, although the intensity and degree of integration of crops and livestock may strongly vary across smallholder farms. Powell et al. (2004) reported that this farming system produces most of the principal cereals (maize, sorghum, pearl millet and rice) and legumes (cowpea and peanut) of households in Sub-Saharan Africa (SSA). Similarly, the primary crop types cultivated by farmers in our study area fall within the broad categories of cereals, legumes, and vegetables (Lenhardt et al., 2014; MoFA, 2022a). Therefore, management practices that affect crop yields in MCLS have great implication for food security within the region. Among all the management strategies considered, fertilization has been suggested as a promising approach for enhancing crop yields (Cai et al., 2019; Liu et al., 2021).

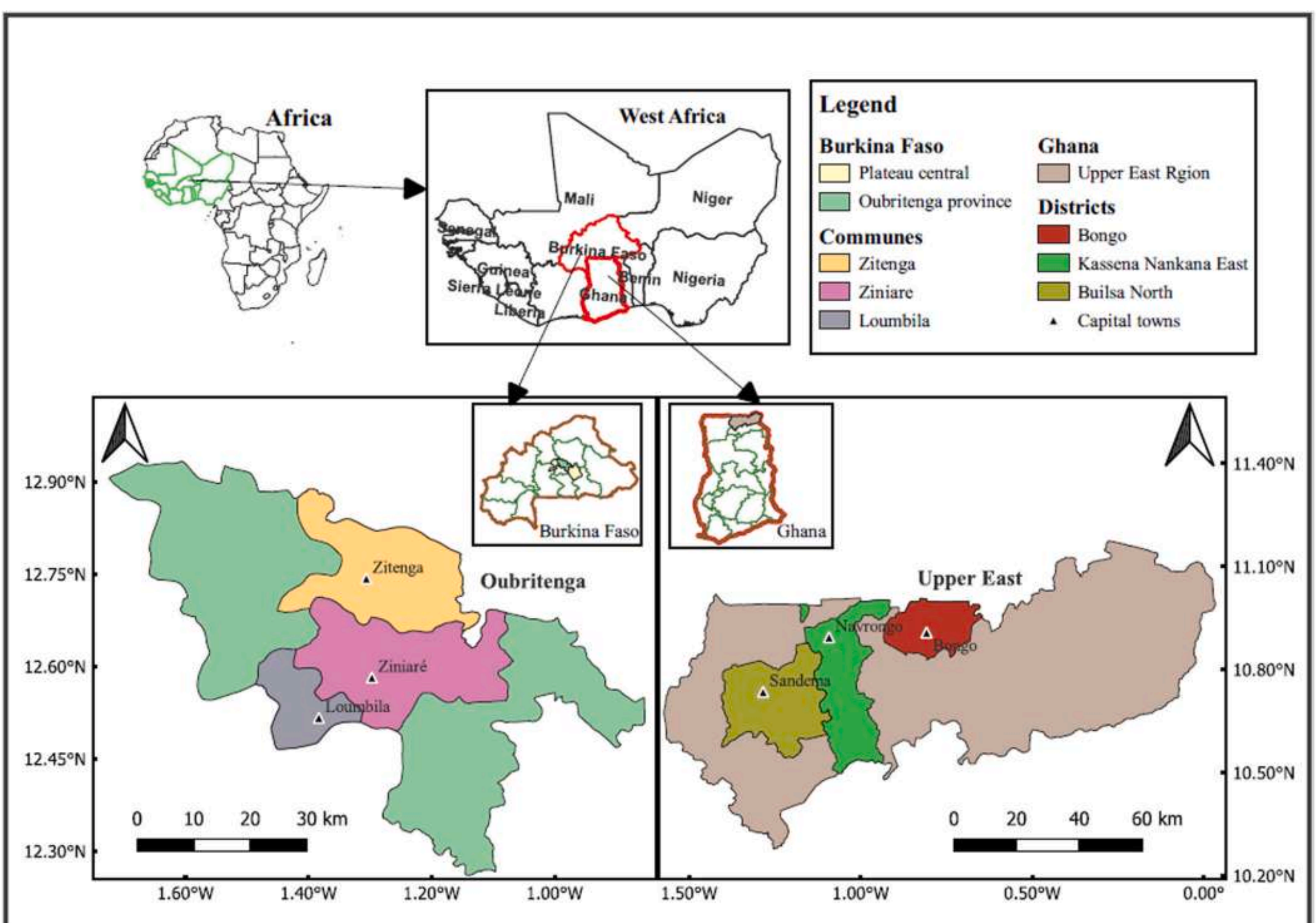

Fig. 2. A map showing the communes and districts where the surveys were conducted in Burkina Faso and Ghana, respectively.

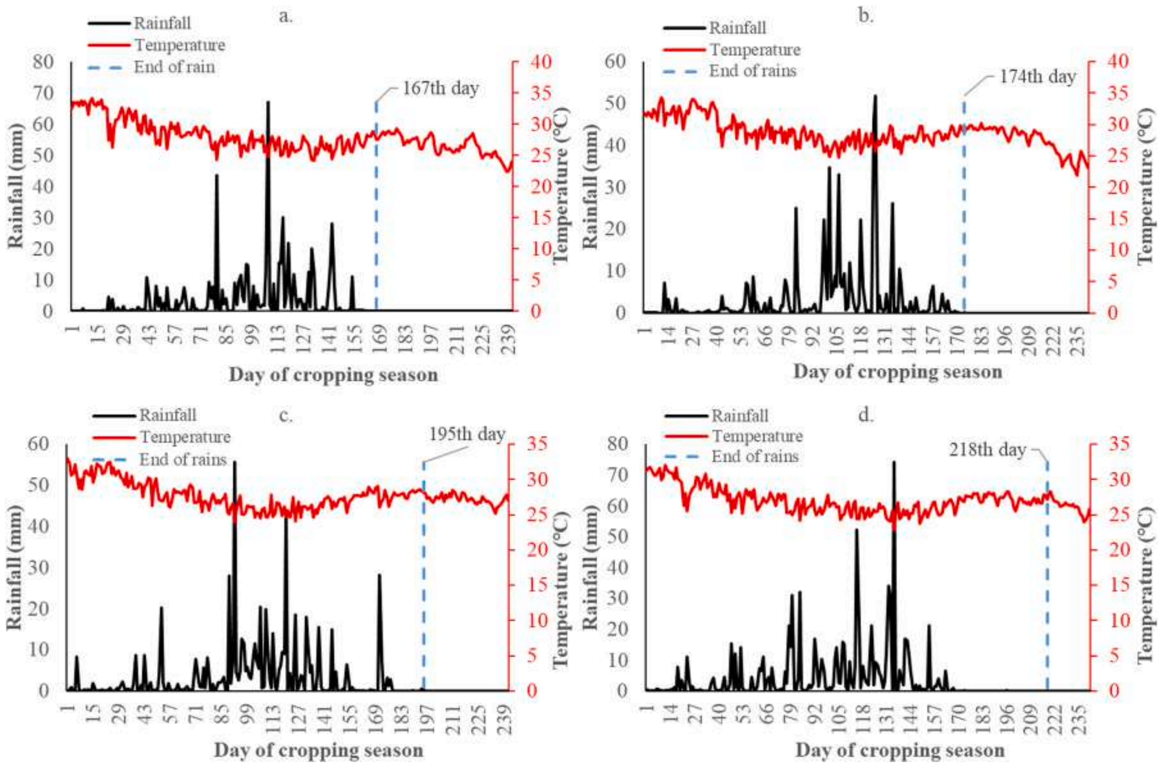

Fig. 3. Daily rainfall and temperature of surveyed communes in Burkina Faso (a) 2022, (b) 2023 and districts in Ghana (c) 2021 and (d) 2022. The dotted vertical line marks the final day of rainfall in the cropping season.

Maintaining soil fertility with the application of manure, had been a common practice among smallholder MCLS farmers for many centuries (McIntire et al., 1992; Powell, 2014). Numerous researchers had shown that manure application can improve soil quality and crop yields (Garba et al., 2018; Rahman et al., 2019). But recently, manure is not consistently or sufficiently applied by all farmers (Adjogboto et al., 2023), even in MCLS that permits its use. This is due to several socio-economic and biophysical constraints. For instance, high manure application rates needed to counterbalance nutrient mining by crops on low fertility soils in the Sudan savannah zones may not be feasible or economical for resource-constrained farmers (Sileshi et al., 2019). Moreover, the application of manure in arable cropland is labour-demanding (Bijay-Singh and Craswell, 2021). Consequently, as the farm size or distance between the homestead and cropland increases, there is a reduction in the quantity of manure transported and applied. Conversely, in cases where manure is optimally applied, it is rarely done on time or incorporated into the soil, thereby exposing it to environmental conditions (e.g. temperature, rainfall, humidity, wind) that are known to affect nutrient loss rates from manure (Waithaka et al., 2007; Owen and Silver, 2017). For instance, when manure is incorporated within 8 hours, approximately 90 % of its nitrogen (N) becomes available to plants, comparing with 40 % N availability when incorporation is delayed until 5–7 days later (Paul et al., 2013). These circumstances likely contributed to the modest improvement in crop yields following manure application (Sileshi et al., 2017), potentially prompting MCLS farmers to consider substituting or supplementing their nutrient source with chemical fertilizers.

The combined use of manure and chemical fertilizers offers an alternative approach to sole manure application to achieve high crop yields, improve the soil environment and soil quality (Martínez et al., 2017; Wang et al., 2017). In most cases, this combined approach leads to significant increases in yield primarily because of the increased total nutrient inputs (Sheikha, 2016; Berdjour et al., 2020). However, the proportion of this combination (manure + chemical fertilizer) might differ among farmers engaged in MCLS. This variation depends on the quantity of accessible manure, affordability of chemical fertilizer, and the number of cropland requiring fertilization. In MCLS, the application of both manure and chemical fertilizer is said to be additive when 100 % of the recommended rate of manure was combined with a given amount N fertilizer (e.g., 25, 50, 75 etc. kg ha^{-1}) irrespective of the nutrient content of the manure (Vanlauwe et al., 2011). Whereas the application of both fertilizers is said to be substitutive when a given proportion (e.g., 50 %) of the recommended rate of N was substituted with chemical fertilizer input (Vanlauwe et al., 2011). Therefore, to understand the nutrient management approach of MCLS farmers in the Sudan Savannah zone, the nutrient contributions (source and amount) should be investigated and reported. Additionally, time and the method of fertilizer placement should be assessed to identify efficient utilization of soil-applied nutrients that increase crop yields and at the same time minimize the environment impact of fertilizer application. However, detailed evaluations of fertilizer management practices under real-world farmer's conditions, have not been previously undertaken in MCLS in Burkina Faso, Ghana, or other areas of the Sudan Savannah of West Africa.

To fill these knowledge gaps and provide a basis for better nutrient management of crops in MCLS, a farmer survey on crop-livestock production and management was conducted in Burkina Faso and Ghana. The objective was to understand and quantify the potential impact of current fertilizer application practices in smallholder MCLS in Ghana and Burkina Faso for identifying opportunities to improve crop yields and enhance smallholder MCLS farmers' livelihoods. In this paper the term smallholder farmer denotes those with small (< 2 ha) and fragmented land holdings, limited access to inputs, less than 50 small ruminant, or less than 25 cattle or less than 1000 poultry (MOFA/DFID, 2002; Chamberlin, 2007).

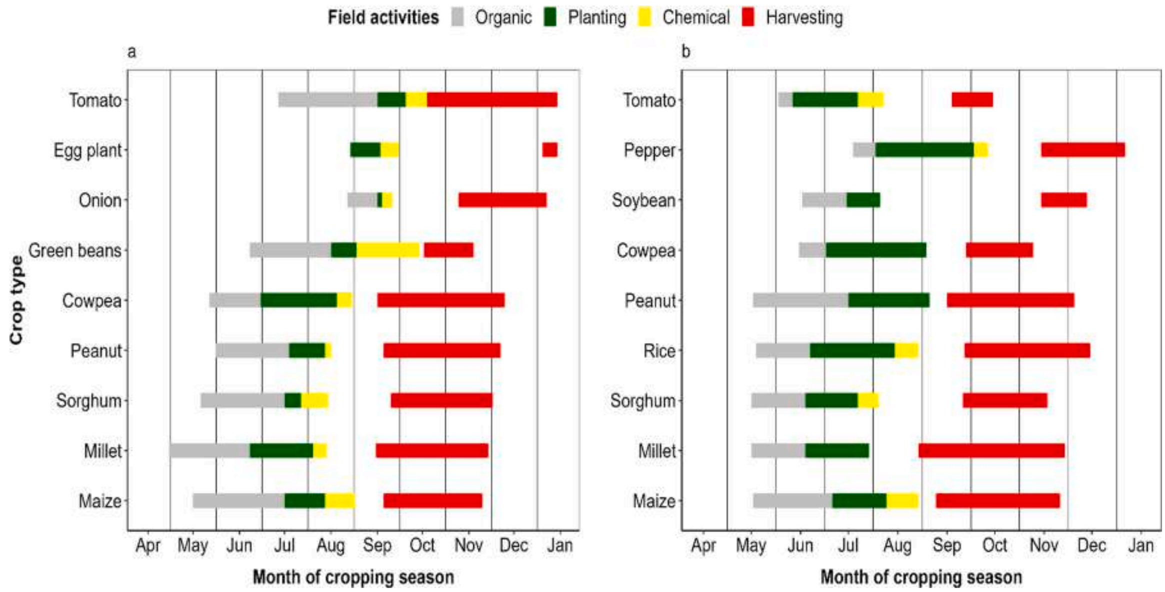

Fig. 4. Cropping calendar depicting the start and end dates of cropping seasons for grain and vegetable crops in mixed crop-livestock farms in Burkina Faso (a) and Ghana (b).

2. Materials and method

2.1. Study area

Farm surveys were conducted in the Loumbila, Ziniaré, and Zitenga communes of the Oubritenga province of Burkina Faso, as well as in the Kassena Nankana, Builsa North and Bongo districts of the Upper East Region of Ghana (Fig. 2). For the purposes of this study, these locations are collectively referred to as Burkina Faso and Ghana. These surveys covered the 2021/2022 (Ghana) and 2022/2023 (Burkina Faso) cropping seasons (i.e., the annual cycle of crop production activities). Daily mean temperature (℃) and rainfall (mm) data were obtained from the fifth generation of Agrometeorological European Reanalysis (AgERA5) through the Copernicus climate data store (Boogaard et al., 2020). Temperature (℃) and rainfall (mm) data are presented as the mean values for all study areas within each country. In Ghana, the total rainfall recorded during 2021 was 625.80 mm and 2022 was 830.66 mm (Fig. 3c-d), and the mean temperatures for 2021 and 2022 were 27.6 ℃ and 27.0 ℃, respectively. In Burkina Faso, the total rainfall recorded was 608.20 mm in 2022 and 529.47 mm in 2023 (Fig. 3a-b), whilst the mean temperatures were 27.8 ℃ in 2022 and 28.5 ℃ in 2023 (Fig. 3a-b). The dominant soils in the study areas of Ghana are Lixisols, characterized by topsoil (0–30 cm) properties of pH 6.3 (H_2O), organic carbon (OC) 0.53 % (by weight), total exchangeable bases (TEB) 4.0 cmol kg^{-1}, cation exchange capacity (CEC) 4.0 cmol kg^{-1}, and a sandy-loam texture (Nachtergaele et al., 2023). Similarly, the study areas in Burkina Faso have soils belonging to the Plinthosols group, with topsoil (0–30 cm) properties of pH 5.9 (H_2O), OC 0.50 % (by weight), TEB 4.5 cmol kg^{-1}, CEC 5.0 cmol kg^{-1}, and a sandy-loam texture (Nachtergaele et al., 2023).

2.2. Survey procedure

In Burkina Faso and Ghana, ten and five enumerators, respectively, were trained and conducted the surveys. Using face-to-face interviews, information from farmers was recorded using a digital questionnaire hosted on the KoboToolBox platform and deployed via KoBoCollect v2023.1.2 for Burkina Faso and v2022.2.3 for Ghana. Data were collected from 101 MCLS farmers (58 in Burkina Faso and 43 in Ghana), encompassing a total of 361 fields (143 fields in Burkina Faso and 218 fields in Ghana). For each farmer field agronomic management information was gathered through both questionnaires and field measurements. For example, crop yield data for the first year's cropping season in each study area were obtained from farmers' responses to the questionnaire, while yields for the second year's cropping season were measured from a 5 × 5 m subplot within each main plot (farm). This process involved two field visits: the first to establish the 5 × 5 m quadrat with field pegs and record field information (coordinate points and area in square meters (sqm)), and the second for harvesting and weighing the yield from the subplot. In cases where crops had reached physiological maturity by the time of data collection (e.g., millet, which is planted early), a single visit sufficed to collect all required information.

Following the survey, a review of each individual crop field for data completeness resulted in the exclusion of 44 fields. This exclusion was necessary due to the inaccessibility of certain fields, which prevented the recording of data on coordinates, area (sqm), and yield. Similarly, seven

Table 1
Farm sample characteristics for mixed crop-livestock farmers in Burkina Faso and Ghana.

	Burkina Faso		Ghana	
	Mean	Standard deviation	Mean	Standard deviation
Cropland area (ha)	0.31	0.53	0.18	0.16
Grain crops	0.36	0.57	0.19	0.17
Maize	0.27	0.29	0.18	0.15
Millet	0.41	0.38	0.12	0.08
Sorghum	0.29	0.33	0.18	0.23
Rice	-	-	0.23	0.19
Peanut	0.59	1.08	0.22	0.17
Cowpea	0.32	0.61	0.15	0.06
Soybean	-	-	0.12	0.06
Green beans	0.36	0.38	-	-
Vegetable crops	0.08	0.09	0.09	0.09
Tomato	0.09	0.08	0.04	0.01
Egg plant	0.01	0.00	-	-
Pepper	-	-	0.13	0.10
Livestock number	20.5	26.9	19.8	27.7
Cattle	8.6	10.4	7.6	4.6
Sheep	14.2	9.1	11.4	17.1
Goat	11.5	7.1	10.7	6.6
Pig	15.0	1.4	12.1	20.8
Poultry	40.1	40.8	46.0	39.3

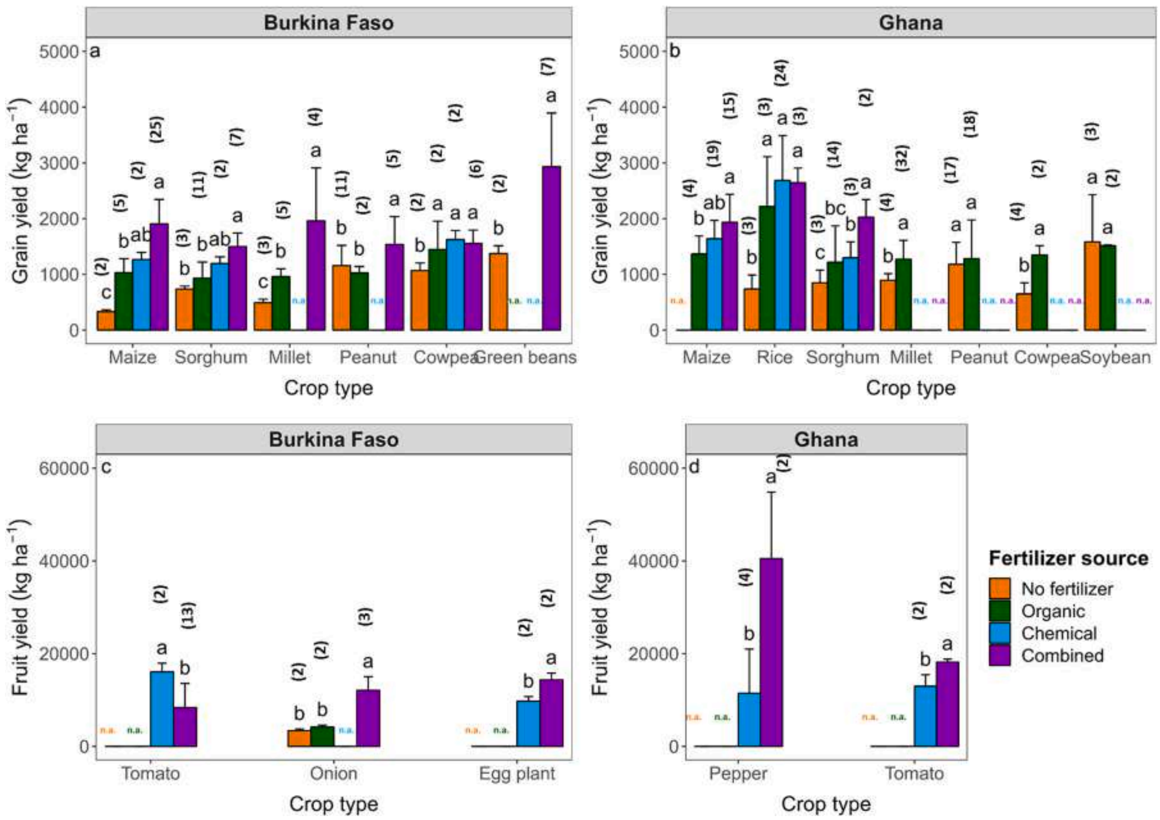

Fig. 5. The effect of fertilizer source on grain (a – b) and fruit (c – d) yield in Burkina Faso and Ghana, respectively. Values are means of two cropping seasons. Sample size of each mean in brackets. Error bars represent the standard deviation. Values under each crop type with the same letter are not significantly different from each other at the $P < 0.05$ level. "n.a" indicates missing data on fertilizer source level for a crop type.

(7) fields were excluded due to a small sample size ($n = 1$) for crops such as rice, sesame, zucchini, cucumber, and carrot in Burkina Faso, and Bambara groundnut, and eggplant in Ghana. Additionally, a root and tuber crop; sweet potato ($n = 3$) was excluded in Ghana. Consequently, the data for this study comprised 307 individual grain and vegetable crop fields, with 123 fields from Burkina Faso and 184 from Ghana. Summary statistics for the final sample of farms are presented in Table 1.

2.3. Data collection

Each of the 307 crop fields were delineated using a Global Positioning System (GPS) to calculate the cultivated area per crop. The collected agronomic management and yield data included; planting time, fertilizer application time, harvesting time, type of chemical fertilizer used, amount of fertilizer applied (kg plot^{-1}), method of fertilizer placement (broadcast versus side placement versus furrow), weight of grain or fruit (kg per 25 m^2). To determine the effect of the agronomic management on yield, we focus on the source of fertilizer, method of fertilizer placement, timing of fertilizer (chemical and manure) application, and the rate of N (kg ha^{-1}) applied.

2.3.1. Fertilizer management

Based on the type of fertilizer(s) used, MCLS farms were categorized into four fertilizer source groups: No fertilizer, manure, chemical fertilizer and combined (manure + chemical fertilizer). The method of fertilizer placement was also recorded and grouped as broadcast, side placement or furrow. The timing of chemical fertilizer and manure application was determined using respectively Eqs. (1) and (2). We assumed an averaged nitrogen (N) content of 1.6 % for manure from cattle + small ruminants + pig + poultry (Sileshi et al., 2017). For chemical fertilizer, the N content was calculated using Eq. (3). Hence the total N applied to a crop field was the sum of the N content in both manure and chemical fertilizer (Eq. (4)).

$$\Delta T = Df - Dp \quad (1)$$

$$\Delta T = Dp - Df \quad (2)$$

The application time was then classified as optimum if $\Delta T \leq Tr$ or late if $\Delta T > Tr$. Where Df is the fertilizer application date, Dp is the planting date, ΔT is the difference between fertilizer application date and planting date (in days), and Tr is the maximum number of days from planting date for the fertilizer application to be considered within the recommended time for each crop type (Table S1). On the other hand, manure application was considered optimum when Tr was between 0 and 3 weeks before planting (WABP).

$$N_{CHEM} = \frac{(Q\ X\ C)}{100} \quad (3)$$

$$N_{TOTAL} = N_{CHEM} + N_{MAN} \quad (4)$$

The N rate (kg ha^{-1}) was considered low if $NTOTAL < NCR$ or recommended if $NTOTAL \geq NCR$. Where $NCHEM$ is the rate of N (kg ha^{-1}) applied through chemical fertilizer application, Q is the quantity of chemical fertilizer (kg) applied, C is the fertilizer grade for N in the applied fertilizer, $NMAN$ is the amount of N in manure, $NTOTAL$ is the total amount of N (kg ha^{-1}) applied, and NCR is the crop type and country specific N rate (kg ha^{-1}) recommendation (Table S2).

The contribution of manure and chemical fertilizer to the total nitrogen (N) rate (kg ha^{-1}) applied to each crop type was determined by summing the amounts of N applied as manure and chemical fertilizer for all surveyed farms. For example, for maize, the total N from both sources was calculated, and then the respective shares of manure and chemical fertilizer within this total were determined.

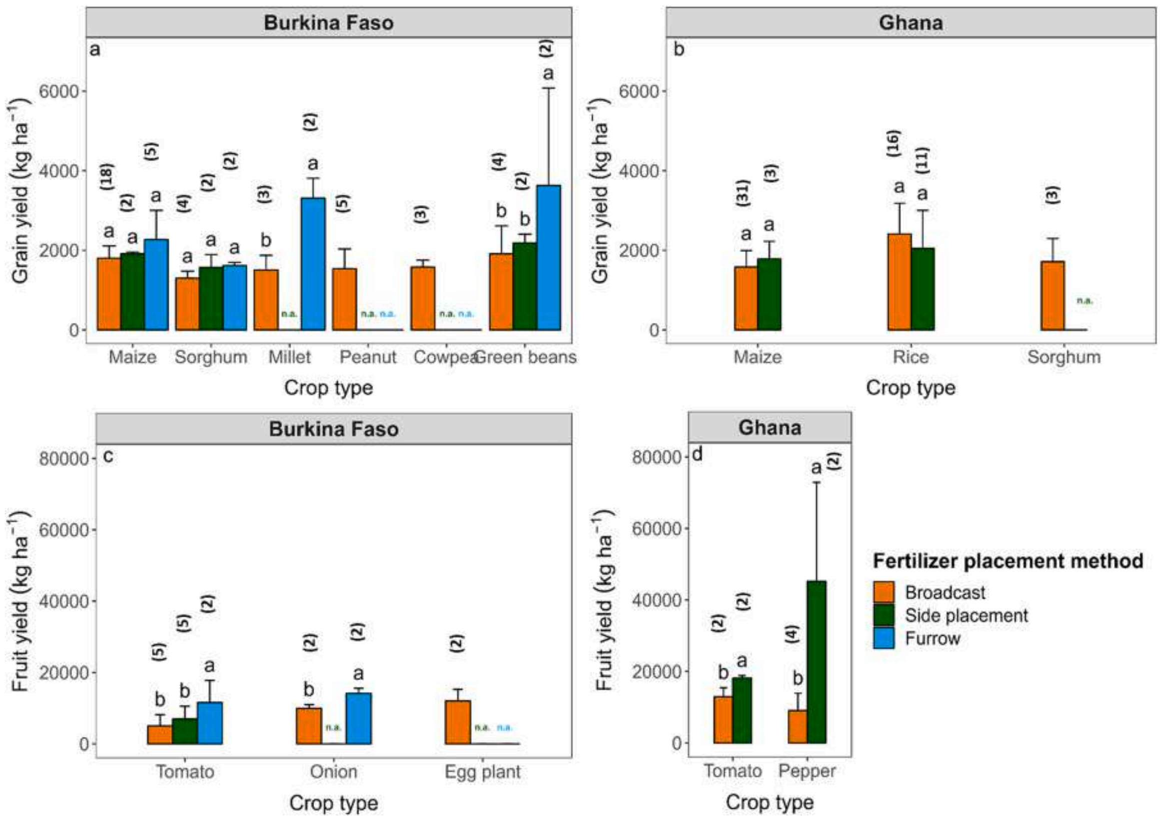

Fig. 6. The effect of fertilizer placement method on grain (a – b) and fruit (c – d) yield in Burkina Faso and Ghana, respectively. Values are means of two cropping seasons. Sample size of each mean in brackets Error bars represent the standard deviation. Values under each crop type with the same letter are not significantly different from each other at the P < 0.05 level. "n.a" indicates missing data on fertilizer placement level for a crop type.

2.3.2. Measurement of yield

The yield of both grain and vegetable crops during the second cropping season was measured from the 5 × 5 m quadrat in each crop field. Grain yields were harvested at physiological maturity and processed (e.g., dehusking, shelling) before measurement. Favorable conditions for drying grains were created by relatively low rainfall and high temperatures during the physiological maturity phase. Similarly, vegetables were harvested at physiological maturity and weighed to determine fruit yield. All yields were then expressed in kg ha^{-1}.

2.4. Statistical analysis

Mean grain and fruit yield were used to evaluate the effects of fertilizer source, method of placement, timing and N (kg ha^{-1}) applied using one-way Analysis of Variance (ANOVA). When ANOVA results were significant, means were compared using Tukey's post-hoc test, with all statistical differences tested at a 5 % probability level or lower ($P \leq 0.05$). To assess the accuracy of the reported yields (farmer estimates) against the actual measured yields, we performed a regression analysis of the reported yields versus the measured yield and used the coefficient of determination (R^2) from the linear model to evaluate the overall agreement between the reported and measured yields. The reported yield closely matched the measured yields, with the following coefficients of determination: for Burkina Faso, grain yield ($R^2 = 0.8$) and fruit yield ($R^2 = 0.85$); and for Ghana, grain yield ($R^2 = 0.5$) and fruit yield ($R^2 = 0.76$)) (Figure S1). All statistical analyses were performed using R statistical software (version 4.3.1).

3. Results

3.1. Effect of fertilizer source on yields

In Burkina Faso, all grain and vegetable crops showed a significant response to fertilizer source (Fig. 5a and c). The combined application of chemical fertilizer and manure resulted in the highest ($P < 0.05$) grain yields: 1905 kg ha^{-1} for maize, 1501 kg ha^{-1} for sorghum, 1959 kg ha^{-1} for millet, 1538 kg ha^{-1} for peanut, and 2932 kg ha^{-1} for green beans. While the yield for cowpea under chemical fertilizer was greater, it was not significantly different from the yield obtained with the combined fertilizer application. Similarly, higher ($P < 0.05$) fruit yields were recorded under combined application of fertilizer for onion (12,087 kg ha^{-1}) and eggplant (14,370 kg ha^{-1}). Conversely, when chemical fertilizer was applied alone, tomato produced the highest ($P < 0.05$) fruit yield of 16,075 kg ha^{-1} (Fig. 5c).

In Ghana, with the exception of peanut and soybean, fertilizer source significantly influenced yields in both grain and vegetable crops (Fig. 5b and d). For grain crops, the combined application of chemical fertilizer and manure resulted in increased ($P < 0.05$) yields of 1935 kg ha^{-1} for maize and 2025 kg ha^{-1} for sorghum. Rice showed a response of 2685 kg ha^{-1} when chemical fertilizer was applied alone. However, for crops such as millet and cowpea, in the absence of chemical fertilizer or combined, the application of manure alone was sufficient to produce a significant yield response compared to plots with no fertilization (Fig. 5b). In vegetable crops, the combination of manure and chemical fertilizer had an additive effect, resulting in increased ($P < 0.05$) fruit yields of 18,180 kg ha^{-1} for tomato and 40,500 kg ha^{-1} for pepper (Fig. 5d).

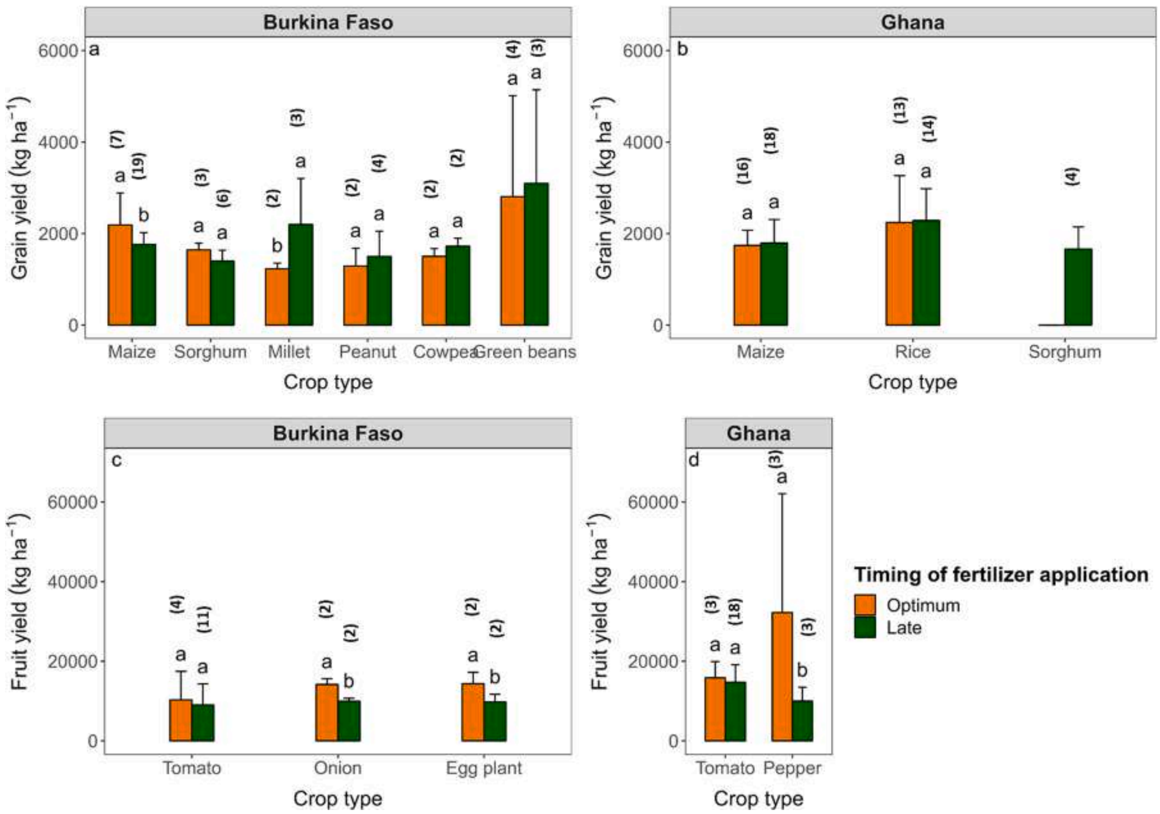

Fig. 7. The effect of timing of chemical fertilizer application on grain (a – b) and fruit (c – d) yield in Burkina Faso and Ghana, respectively. Values are means of two cropping seasons. Sample size of each mean in brackets. Error bars represent the standard deviation. Values under each crop type with the same letter are not significantly different from each other at the P < 0.05 level. "n.a" indicates missing data on fertilizer timing level for a crop type.

3.2. Effect of fertilizer placement on yields

Fig. 6 shows the effect of fertilizer placement methods on grain and fruit yields. In Burkina Faso, the furrow method of fertilizer application, where practiced, resulted in either significantly higher ($p < 0.05$) or numerically greater grain and fruit yields compared to broadcasting and side placement of fertilizer (Fig. 6a and c). In Ghana, grain yields did not significantly respond to different fertilizer placement methods (Fig. 6b). However, in vegetable crops, there was a significant variation in yields based on the fertilizer placement method. Side placement of fertilizer resulted in the highest fruit yield, with an average increase of 40 % for tomato and 398 % for pepper compared to broadcasting (Fig. 6d).

3.3. Effect of fertilizer application timing on yields

The effects of the timing of chemical fertilizer and manure application are shown in Figs. 7 and 8, respectively. In Burkina Faso, applying chemical fertilizer at the optimum time significantly increased ($p < 0.05$) maize yield by 24 %, onion yield by 42 %, and eggplant yield by 31 % (Fig. 7a and c). Conversely, late application of chemical fertilizer significantly increased ($p < 0.05$) millet yield by 78 % (Fig. 7a). The timing of manure application had a significant impact, with yield responses for sorghum (75 %), millet (81 %), green beans (78 %), and tomato (61 %) being significantly higher when manure was applied within the optimum period compared to late application (Fig. 8a and c).

In Ghana, no significant yield response was observed for grain crops under the different timing of chemical fertilizer application (Fig. 7b). However, when chemical fertilizer was applied within the optimum period for pepper, fruit yield increased ($p < 0.05$) from 10,033 kg ha^{-1} to 32,240 kg ha^{-1}. Conversely to our findings on manure application timing in Burkina Faso, delayed application of manure in Ghana increased ($p < 0.05$) grain yields of rice by 16 %, millet yield by 20 % and fruit yield of pepper by 238 % compared to early (optimum) application of manure (Fig. 8b and d).

3.4. Effect of applied N (kg ha^{-1}) on yields

As shown in Fig. 9a, in Burkina Faso, yields of sorghum, cowpea and green beans were significantly influenced ($p < 0.05$) by the rate of nitrogen (N) applied, such that when compared with low application rates, applying the recommended rate increased yields by 36 %, 52 % and 86 %, respectively. However, due to the lack of data on the recommended N rate for onion and eggplant, formal statistical testing between recommended and low N rates was not feasible (Fig. 9c). Additionally, with the exception of tomato and onion, which received 66 % of their N input from chemical fertilizers, the primary source of N input for all other crops was from manure (Fig. 10).

In Ghana, grain crops such as rice, sorghum, millet, and cowpea showed a significant response to the rate of nitrogen (N) applied (Fig. 9b). Applying N at the recommended rate resulted in higher ($p < 0.05$) grain yields compared to the low N application rate (Fig. 9b). Although the recommended N application did not result in significant differences for other grain crops, it generally showed a tendency to increase yields. However, due to the small sample size for the recommended N rate, statistical testing for tomato yields was not feasible (Fig. 9d). Interestingly, N input from manure constituted the entire N input for millet, peanut, cowpea, and soybean (100 % of their N input). Conversely, the contribution of chemical fertilizers to N inputs per hectare was highest in maize, rice, and pepper (Fig. 10).

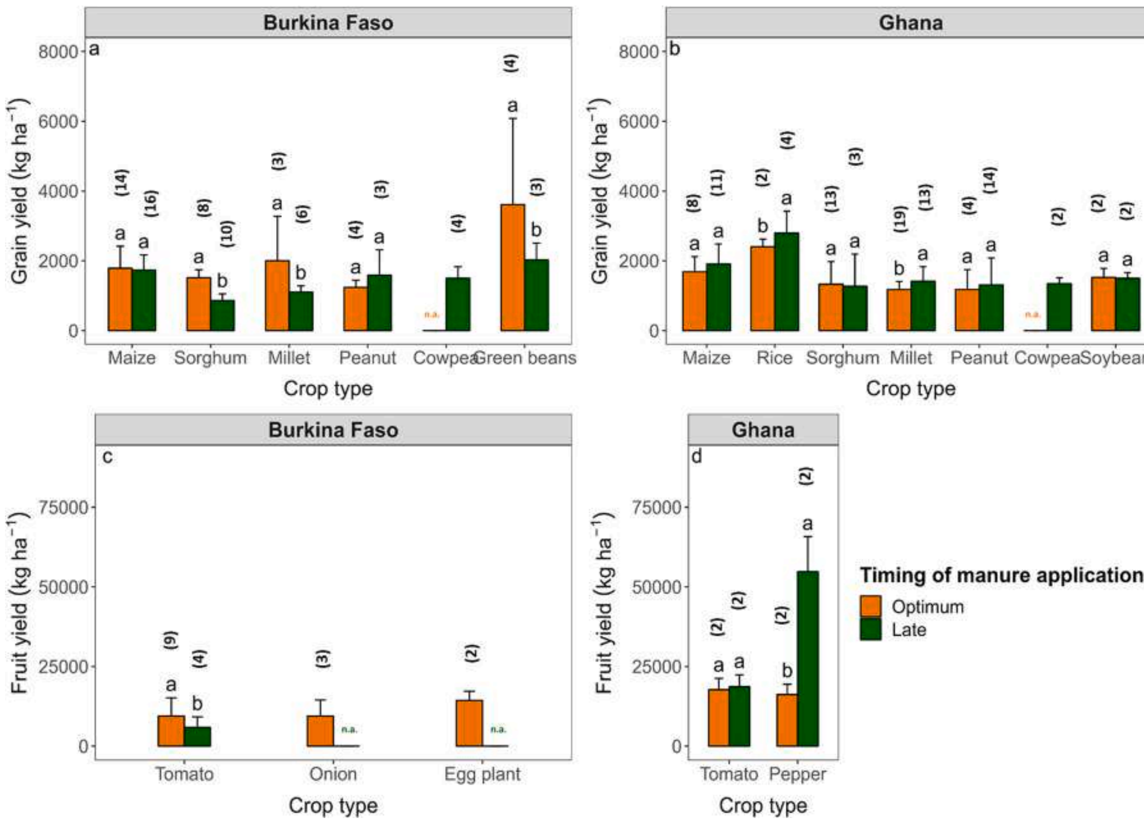

Fig. 8. The effect of timing of manure application on grain (a – b) and fruit (c – d) yield in Burkina Faso and Ghana, respectively. Values are means of two cropping seasons. Sample size of each mean in brackets. Error bars represent the standard deviation. Values under each crop type with the same letter are not significantly different from each other at the $P < 0.05$ level. "n.a" indicates missing data on manure application timing level for a crop type.

4. Discussion

4.1. Effect of fertilizer source on yields

In most crops and both countries, the combined application of manure and chemical fertilizers resulted in significantly higher yields compared to the control (no fertilizer) and the application of either manure or chemical fertilizer alone. These findings align with Wei et al. (2016), who reported that the combined application of manure and chemical fertilizer significantly increased yields of grain crops (maize, rice, and wheat) by an average of 129 % compared to no fertilizer (control), 29.6 % compared to manure application only, and 7.6 % compared to chemical fertilizer only. Khalid et al. (2014) and Geremew et al. (2019) also observed higher tomato fruit yields with combined manure and chemical fertilizer applications, attributing the positive effect to improved soil nutrient status. Despite the absence of chemical fertilizer alone or in combination with manure for millet and cowpea in Ghana (Fig. 5b), manure application alone significantly improved grain yield compared to their no fertilizer MCLS farms. Nonetheless, the yield advantage remained below the national average yield for millet (1500 kg ha^{-1}) and cowpea (1670 kg ha^{-1}) (MoFA, 2022b). The lack of synchronization between the timing of manure application and the crop's critical nutrient uptake periods may contribute to the observed results. Most farmers in Northern Ghana apply manure at least one month before planting their crops, which may not align with the crop's nutrient needs during key growth stages. Therefore, applying organic manure alone might not be sufficient to achieve sustainable yield increases for MCLS farmers or farmers with similar practice.

4.2. Effect of fertilizer placement on yields

As observed among farmers surveyed in this study, their method of broadcasting and side placement of fertilizer (ie., surface banding without incorporation) are all subject to the same environmental conditions (e.g. temperature, rainfall, humidity, wind) that are known to affect nutrient loss rates from fertilizer (Waithaka et al., 2007; Owen and Silver, 2017). In furrow application, fertilizers are placed in bands and covered with soil in continuous trenches or furrows near the crop rows. Consequently, in Burkina Faso, broadcasting and side placement of fertilizer, generally resulted in decreased grain and vegetable crop yields compared to the furrow application method (Fig. 6a and c). This can be attributed to the higher nutrient losses through volatilization and soil erosion associated with surface applications. In contrast, furrow application, a sub-surface fertilizer placement method, has been reported to enhance nutrient uptake and yield. Research indicates that crop roots tend to proliferate around the fertilizer zone, with deeper placement promoting root density and nitrogen uptake (Li et al., 2009). Previous field studies have shown that deep fertilizer placement (> 10 cm), as opposed to surface applications, significantly increases yields and improves nitrogen use efficiency (Nkebiwe et al., 2016; Rychel, 2023). In confirming this, Wang et al. (2022) reported that deep urea placement promoted deep root proliferation in winter wheat, enhancing nitrogen uptake and water utilization.

Conversely, when furrow application was missing, the significantly higher fruit yields that was achieved with side-placement (surface banded) in Ghana, can be primarily attributed to a more suitable alignment between the frequency of side-placed fertilizer applications and nutrient availability. Unlike other grain crops in Ghana, pepper and tomato are the only crops to which smallholder farmers within the study area apply chemical fertilizer up to 4 times, from the seedling stage to first plucking (harvest). Numerous studies suggest that it is crucial to optimally match nutrient supply with crop uptake in both time and space to increase nutrient-use efficiency (Chen et al., 2006; Lu et al., 2019). Therefore, to achieve increased yields, MCLS farmers need to

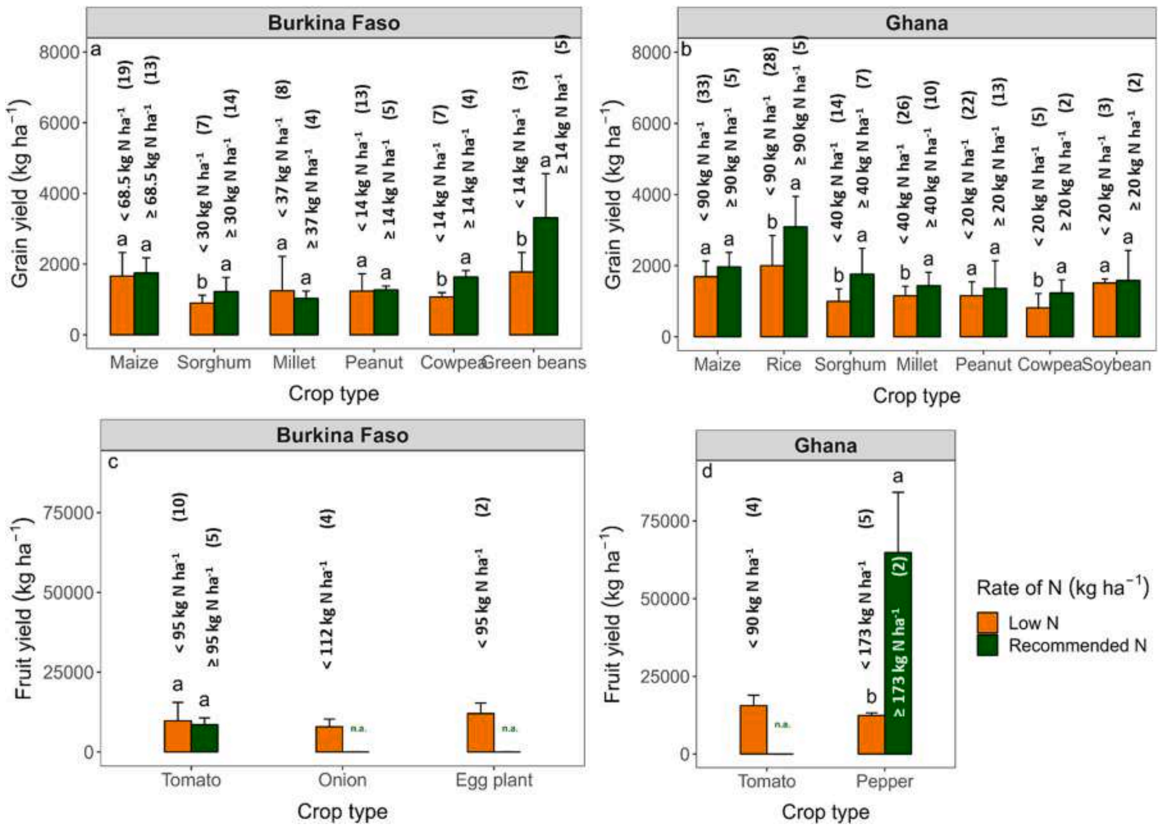

Fig. 9. The effect of N rate (kg/ha) applied on grain (a – b) and fruit (c – d) yield in Burkina Faso and Ghana, respectively. Values are means of two cropping seasons. Sample size of each mean in brackets. Error bars represent the standard deviation. Values under each crop type with the same letter are not significantly different from each other at the $P < 0.05$ level. "n.a" indicates missing data on N rate level for a crop type.

consider the benefits of the different frequencies and stages of fertilizer application against the costs of additional field activities.

4.3. Effect of fertilizer application timing on yields

The correct timing of fertilizer application can lead to nutrient availability, optimum growth and improve crop yields (Mosisa et al., 2022). However, an interesting finding from this analysis is that few crops responded significantly to the timing of chemical fertilizer application, and even among these, the results did not consistently favor the optimum timing. For example, sorghum responded better to late application. Several factors may account for this finding. According to Marenya and Barrett (2009), on farmers' fields, inorganic fertilizer becomes less effective when soil organic matter is low, regardless of the application timing. Additionally, looking at the disadvantages associated with the fertilizer application methods (broadcast and side-placement) by farmers in our study area, either a major rainfall event or temporal cessation of same just after fertilization, may have reduced the response to the timing of chemical fertilizer application. Variations in genotype can also influence crop response to fertilization. For instance, in defining fertilization strategies for sorghum in the Sudano-Sahelian climate of Senegal, Ganyo et al. (2019) found that long-cycle genotypes benefited more from late fertilization compared to short-cycle genotypes. Similarly, Kante et al. (2017) reported variable grain yields in sorghum in Mali based on the type of genetic material (tall, short hybrids, and landrace). As a result, site and genotype-specific recommended timing of fertilizer application could be more important than blanket recommended.

On the other hand, some grain yields responded differently to the timing of manure application in both countries. In Burkina Faso, the optimum timing of manure application significantly improved the yields of sorghum, millet, green beans, and tomato. Conversely, in Ghana, late manure application significantly enhanced rice, millet, and pepper yields. These differing responses to manure application timing may be attributed to several interacting factors: (1) decomposition rates, (2) nutrient release rates, and (3) the animal source of the manure (Chikowo et al., 2010; Sileshi et al., 2017). According to Sileshi et al. (2017), the rate of N release over time varies with the animal source. For example, during the first year of application, 32 %, 75 %, and 90 % of N in manure from cattle, poultry, and pigs, respectively, is available (Eghball et al., 2002). In addition, even though all crops require the same mineral elements, the timing of uptake and the desired nutrient needed at each growth stage vary by crop type (Jones et al., 2015). Therefore, farmers practice of applying manure to fields for different crop types simultaneously may not match the desired nutrient availability and crop uptake requirement. Thus, the varying effects of manure application timing observed in our study can be explained by these insights.

4.4. Effect of applied N (kg ha^{-1}) on yields

Variation in grain yield response to nitrogen (N) application rates between countries and crop types was observed (Fig. 9). In Burkina Faso, sorghum, cowpea and green bean yields significantly responded to the recommended N rate, while in Ghana, the grain yields of rice, sorghum, millet, and cowpea were significantly influenced by their specific recommended N rates. This response pattern is expected, given that the effect of N application on crop yield depends on several factors. Weather, particularly rainfall in dryland crop production areas, is a primary driver of both crop growth and soil nutrient availability, with drastic year-to-year variability (Arnall et al., 2013; Mosisa et al., 2022). Our findings from Fig. 3, support this assertion. Similarly, in exploring the causes of poor crop responses to applied N on African soils, Sileshi

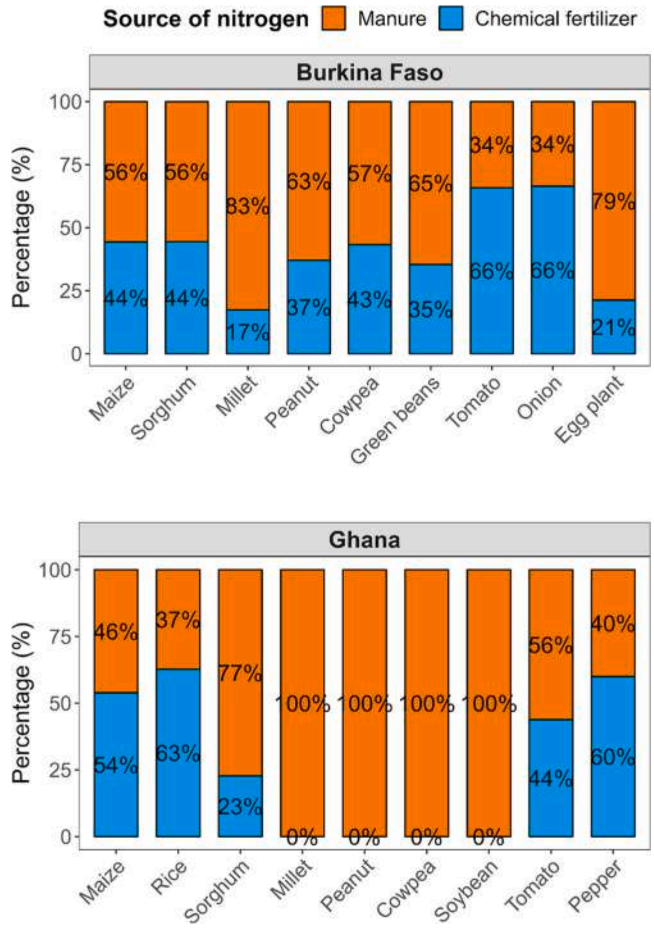

Fig. 10. Contribution of manure and chemical fertilizer to the rate of N (kg/ha) applied to crop type in MCL system farms.

et al. (2022) identified soil type as a crucial determinant. According to the authors, the major soil types in our study area—Plinthosols in Burkina Faso and Lixisols in Ghana—are poorly responsive to NPK fertilizers. Additionally, the different pH levels of these soils will result in varying N availability (Wibberley, 2006).

From Fig. 10, it is evident that the most important source of nitrogen (N) in MCLS was applied through manure. However, in this study, the amount of N in manure was estimated as a percentage (1.6 %) of the total quantity of manure dry matter applied, which may not necessarily reflect the actual N content. This is because the N content in manure is influenced by several factors. Open-air heaps used for storing manure by farmers in our study area (data not shown) and application of same to fields at the onset of the rainy season, as shown in Fig. 3, result in more than 50 % N loss through volatilization and leaching (Rufino et al., 2011). Similarly, Chikowo et al. (2010) reported that the recovery efficiency of manure N is very low (median: 0.19 kg N kg^{-1}) across Sub-Saharan Africa. Consequently, despite the high quantities of manure applied per MCLS cropland (Table S3) and its major contribution to nitrogen (N) (Fig. 10), the observed nutrient losses and low recovery efficiencies may have influenced our yield results (Fig. 9). This is reflected in the variable (weak and strong) correlations between N applied and crop yields in Burkina Faso: sorghum ($R^2 = 0.07$), green beans ($R^2 = 0.05$), cowpea ($R^2 = 0.57$) and in Ghana: sorghum ($R^2 = 0.26$), millet ($R^2 = 0.23$), cowpea ($R^2 = 0.59$), rice ($R^2 = 0.30$), and pepper ($R^2 = 0.86$) (Figure S2). On the other hand, the absence of data for onion, and eggplant in Burkina Faso and tomato in Ghana on recommended N rates (Fig. 9) indicate that the addictive application of chemical fertilizer and manure (Fig. 10; Table S3) in these vegetable crops was insufficient to meet their specific recommended N.

5. Limitations of our study

Our study was not without uncertainties. As shown in Fig. 4, the temporal variation in major farming activities in surveyed farms may have exerted varying effects on grain and vegetable crop yields, indicating that the results of this study should be interpreted with caution. For instance, late planting has been reported to significantly decrease yields in farmers' fields (Kihara et al., 2015). Additionally, the highly heterogeneous crop varieties among the surveyed farmers may present a challenge in precisely estimating crop yield responses to fertilizer application. Beyond the source, timing, method of placement, and amount of nitrogen (N) applied, variations in soil fertility and agronomic management, including the timing of weeding, are key factors responsible for yield variability within individual farms (Tittonell et al., 2008; Giller et al., 2011). Another source of uncertainty in our yield findings arises from variability in climatic factors, specifically rainfall and temperature (Fig. 3), experienced by crops of the same type due to differences in planting dates (Fig. 4). Many of the crop types in our study have specific (climate) requirements for successful establishment and optimal performance during the vegetative and reproductive stages. Thus, the timing at which a crop progresses through its growth stages and encounters these specific climate requirements can significantly influence yield. Nonetheless, this study can be viewed as the beginning of quantitatively analyzing the effect of fertilizer application on grain and vegetable crops in the mixed crop-livestock systems (MCLS) of West Africa. Additionally, we have demonstrated that it is feasible to make precise estimations of crop yield from farmers' estimates and field measurements in smallholder mixed crop-livestock systems.

6. Conclusion

Collectively, the results of this study indicate that:

1. In MCLS, no substantial reduction in grain and vegetable yields was observed when manure and chemical fertilizer were applied in combination.
2. Fertilizer application in furrows has shown a strong potential to enhance grain and vegetable yields, suggesting that subsurface application may be advantageous for improving yields even under adverse weather conditions such as drought or excessive rainfall.
3. High variability characterized yield responses to the blanket recommended timing of chemical fertilizer application for specific crop types. This implies that farmers need to adapt the timing of chemical fertilizer to meet the maximum nutrient demands or growth stage of their crops.
4. The effect of manure application timing varied across locations, indicating differences in nutrient composition and decomposition rates.
5. Yield gains with the amount of N applied did not correspond to the high N contribution from manure, confirming the variability in nutrient content and decomposition rates of manure used by MCLS farmers in our study.

These results suggest that, in addition to an integrated approach to fertilizer management including the appropriate source of fertilizer, method of placement, timing of application, and N rate, farm-specific agronomic management practices are necessary to ensure effective utilization of soil-applied nutrients. Additionally, the timing of fertilizer application must be based on an understanding of manure stoichiometry (Sileshi et al., 2017), crop genotype, and growth stage rather than following a calendar date.

CRediT authorship contribution statement

Berdjour Albert: Writing – original draft, Methodology, Formal analysis, Data curation. **Kumar Srivastava Amit:** Writing – review &

editing, Supervision, Methodology, Conceptualization. **Ewert Frank:** Writing – review & editing, Supervision, Methodology. **Gaiser Thomas:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Sanfo Safietou:** Writing – review & editing, Supervision, Resources. **Ahamadou Bocar:** Writing – review & editing, Supervision, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127525.

Data availability

Data will be made available on request.

References

Adjogboto, A., Didier Likpètè, D., Nadia Adjouavi Sossa-Vihotogbé, C., et al., 2023. Yield response of African leafy vegetables to combined manure and urea microdosing in West Africa. Biotechnol. Agron. Soc. Environ. 27 74–86. https://doi.org/10.25518/1780-4507.20248.

Arnall, D.B., Mallarino, A.P., Ruark, M.D., et al., 2013. Relationship between grain crop yield potential and nitrogen response. Agron. J. 105, 1335–1344. https://doi.org/10.2134/AGRONJ2013.0034.

Berdjour, A., Dugje, I.Y., Rahman, N.A., et al., 2020. Direct estimation of maize leaf area index as influenced by organic and inorganic fertilizer rates in Guinea Savanna. J. Agric. Sci. 12, 66. https://doi.org/10.5539/JAS.V12N6P66.

Bijay-Singh, Craswell, E., 2021. Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. SN Appl. Sci. 3. https://doi.org/10.1007/S42452-021-04521-8.

Boogaard, H., Schubert, J., De Wit, A., et al., 2020. Agrometeorological indicators from 1979 to present derived from reanalysis. Copernic. Clim. Ghange Serv. Clim. Data Store (CDS). https://doi.org/10.24381/cds.6c68c9bb.

Cai, A., Xu, M., Wang, B., et al., 2019. Manure acts as a better fertilizer for increasing crop yields than synthetic fertilizer does by improving soil fertility. Soil Till. Res. 189, 168–175. https://doi.org/10.1016/J.STILL.2018.12.022.

Chamberlin J. (2007) Defining smallholder agriculture in Ghana: Who are smallholders, what do they do and how are they linked with markets? GSSP Working Paper. 6. International Food Policy Research Institute (IFPRI).

Chen, X., Zhang, F., Römheld, V., et al., 2006. Synchronizing N supply from soil and fertilizer and N demand of winter wheat by an improved Nmin method. Nutr. Cycl. Agroecosyst. 74, 91–98. https://doi.org/10.1007/S10705-005-1701-9/METRICS.

Chikowo, R., Corbeels, M., Mapfumo, P., et al., 2010. Nitrogen and phosphorus capture and recovery efficiencies, and crop responses to a range of soil fertility management strategies in sub-Saharan Africa. Nutr. Cycl. Agroecosyst. 88, 59–77. https://doi.org/10.1007/S10705-009-9303-6/TABLES/7.

Eghball, B., Wienhold, B.J., Gilley, J.E., Eigenberg, R.A., 2002. Mineralization of manure nutrients. J. Soil Water Conserv 57, 470–473.

Ganyo, K.K., Muller, B., Ndiaye, M., et al., 2019. Defining fertilization strategies for sorghum (Sorghum bicolor (L.) Moench) production under sudano-sahelian conditions: options for late basal fertilizer application. Agronomy 9, 697. https://doi.org/10.3390/agronomy9110697.

Garba, M., Serme, I., Maman, N., et al., 2018. Crop response to manure and fertilizer in Burkina Faso and Niger. Nutr. Cycl. Agroecosyst. 111, 175–188. https://doi.org/10.1007/S10705-018-9921-Y.

Geremew, B., Girma, A., Birhanu, B., 2019. Effects of dry bioslurry and chemical fertilizers on tomato growth performance, fruit yield and soil properties under irrigated condition in Southern Ethiopian. Afr. J. Agric. Res 14, 1685–1692. https://doi.org/10.5897/AJAR2019.14372.

Giller, K.E., Tittonell, P., Rufino, M.C., et al., 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agric. Syst. 104, 191–203. https://doi.org/10.1016/J.AGSY.2010.07.002.

Jones, C., Olson-Rutz, K., Dinkins, C., 2011. (2015) Nutrient Uptake Timing by Crops. Montana State University, Montana, USA.

Kante, M., Rattunde, H.F.W., Leiser, W.L., et al., 2017. Can tall guinea-race sorghum hybrids deliver yield advantage to smallholder farmers in west and central Africa? Crop Sci. 57, 833–842. https://doi.org/10.2135/CROPSCI2016.09.0765.

Khalid, A.A., Oppong Tuffour, H., Bonsu, M., et al., 2014. Effects of poultry manure and NPK fertilizer on growth and yield of garden eggs (Solanum melongena) in a sandy soil in Ghana. Int J. Sci. Res Knowl. 2, 257–264. https://doi.org/10.12983/ijsrk-2014-p0257-0264.

Kihara, J., Tamene, L.D., Massawe, P., Bekunda, M., 2015. Agronomic survey to assess crop yield, controlling factors and management implications: a case-study of Babati in northern Tanzania. Nutr. Cycl. Agroecosyst. 102, 5–16. https://doi.org/10.1007/S10705-014-9648-3/FIGURES/6.

Lenhardt A., Glennie J., Intscher N., et al (2014) A greener Burkina: Sustainable farming techniques, land reclamation and improved livelihoods.

Li, S.X., Wang, Z.H., Hu, T.T., et al., 2009. Chapter 3 nitrogen in dryland soils of china and its management. Adv. Agron. 101, 123–181. https://doi.org/10.1016/S0065-2113(08)00803-1.

Liu, Q., Xu, H., Yi, H., 2021. Impact of fertilizer on crop yield and C:N:P stoichiometry in arid and semi-arid soil. Int J. Environ. Res Public Health 18. https://doi.org/10.3390/IJERPH18084341.

Lu, D., Song, H., Jiang, S., et al., 2019. Managing fertiliser placement locations and source types to improve rice yield and the use efficiency of nitrogen and phosphorus. F. Crop Res. 231, 10–17. https://doi.org/10.1016/J.FCR.2018.11.004.

Marenya, P.P., Barrett, C.B., 2009. Soil quality and fertilizer use rates among smallholder farmers in western Kenya. Agric. Econ. 40, 561–572. https://doi.org/10.1111/J.1574-0862.2009.00398.X.

Martínez, E., Domingo, F., Roselló, A., et al., 2017. The effects of dairy cattle manure and mineral N fertilizer on irrigated maize and soil N and organic C. Eur. J. Agron. C. 78–85. https://doi.org/10.1016/J.EJA.2016.10.002.

McIntire, J., Bourzat, D. (Daniel), Pingali, P.L., 1992. Crop-Livestock Interaction in Sub-Saharan Africa. World Bank, Washington, D.C.

MoFA (Ministry of Food and Agriculture) (2022a) Major Crop Commodities: Upper East Region of Ghana. https://mofa.gov.gh/site/directorates/regional-directorates/upper-east-region. Accessed 4 Jan 2025.

MoFA (Ministry of Food and Agriculture) (2022b) Agriculture in Ghana: Facts and figures (2021). Statistics, Research and Information Directorate (SRID), Accra.

MOFA/DFID (2002) The Role of Livestock in Rural Livelihoods in Ghana: Final Report; presented to Ministry of Food and Agriculture (MOFA) and Department for International Development (DFID), Accra,

Mosisa, W., Dechassa, N., Kibret, K., et al., 2022. Effects of timing and nitrogen fertilizer application rates on maize yield components and yield in eastern Ethiopia. Agrosyst. Geosci. Environ. 5, e20322. https://doi.org/10.1002/AGG2.20322.

Nachtergaele, F., van Velthuizen, H., Verelst, L., et al., 2023. Harmonized World Soil Database version 2.0. Food Agric Organ United Nations. https://doi.org/10.4060/cc3823en.

Nkebiwe, P.M., Weinmann, M., Bar-Tal, A., Müller, T., 2016. Fertilizer placement to improve crop nutrient acquisition and yield: a review and meta-analysis. F. Crop Res 196, 389–401. https://doi.org/10.1016/J.FCR.2016.07.018.

Owen, J.J., Silver, W.L., 2017. Greenhouse gas emissions from dairy manure management in a Mediterranean environment. Ecol. Appl. 27, 545–559. https://doi.org/10.1002/EAP.1465.

Paul, S., van der Meer, H., Onduru, D., et al., 2013. Effects of cattle and manure management on the nutrient economy of mixed farms in East Africa: a scenario study. Afr. J. Agric. Res 8, 5129–5148. https://doi.org/10.5897/AJAR10.009.

Powell, J.M., 2014. Feed and manure use in low-N-input and high-N-input dairy cattle production systems. Environ. Res Lett. 9, 115004. https://doi.org/10.1088/1748-9326/9/11/115004.

Powell, J.M., Pearson, R.A., Hiernaux, P.H., 2004. Crop–Livestock Interactions in the West African Drylands. Agron. J. 96, 469–483. https://doi.org/10.2134/AGRONJ2004.4690.

Rahman, N.A., Larbi, A., Opoku, A., et al., 2019. Crop–livestock interaction effect on soil quality and maize yield in Northern Ghana. Agron. J. 111, 907–916. https://doi.org/10.2134/AGRONJ2018.08.0523.

Rufino, M.C., Dury, J., Tittonell, P., et al., 2011. Competing use of organic resources, village-level interactions between farm types and climate variability in a communal area of NE Zimbabwe. Agric. Syst. 104, 175–190. https://doi.org/10.1016/J.AGSY.2010.06.001.

Rychel, K., 2023. Fertilizer Placement for Improved Nitrogen Use Efficiency and Mitigation of N2O Emissions. Swedish University of Agricultural Sciences.

Ryschawy, J., Choisis, N., Choisis, J.P., et al., 2012. Mixed crop-livestock systems: an economic and environmental-friendly way of farming? animal 6, 1722–1730. https://doi.org/10.1017/S1751731112000675.

Sheikha, E., 2016. Mixing manure with chemical fertilizers, why? and What is after? (ISSN 2470-6086). Nutr. Food Technol. Open Access 2. https://doi.org/10.16966/2470-6086.112.

Sileshi, G.W., Nhamo, N., Mafongoya, P.L., Tanimu, J., 2017. Stoichiometry of animal manure and implications for nutrient cycling and agriculture in sub-Saharan Africa. Nutr. Cycl. Agroecosyst. 107, 91–105. https://doi.org/10.1007/S10705-016-9817-7/TABLES/4.

Sileshi, G.W., Jama, B., Vanlauwe, B., et al., 2019. Nutrient use efficiency and crop yield response to the combined application of cattle manure and inorganic fertilizer in sub-Saharan Africa. Nutr. Cycl. Agroecosyst. 113, 181–199. https://doi.org/10.1007/S10705-019-09974-3/FIGURES/7.

Sileshi, G.W., Kihara, J., Tamene, L., et al., 2022. Unravelling causes of poor crop response to applied N and P fertilizers on African soils‡. Exp. Agric. 58, e7. https://doi.org/10.1017/S0014479721000247.

Tittonell, P., Shepherd, K.D., Vanlauwe, B., Giller, K.E., 2008. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya—An application of classification and regression tree analysis. Agric. Ecosyst. Environ. 123, 137–150. https://doi.org/10.1016/J.AGEE.2007.05.005.

Vanlauwe, B., Kihara, J., Chivenge, P., et al., 2011. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant Soil 339, 35–50. https://doi.org/10.1007/S11104-010-0462-7.

Waithaka, M.M., Thornton, P.K., Shepherd, K.D., Ndiwa, N.N., 2007. Factors affecting the use of fertilizers and manure by smallholders: the case of Vihiga, western Kenya. Nutr. Cycl. Agroecosyst. 78, 211–224. https://doi.org/10.1007/S10705-006-9087-X/TABLES/3.

Wang, X., Ren, Y., Zhang, S., et al., 2017. Applications of organic manure increased maize (Zea mays L.) yield and water productivity in a semi-arid region. Agric. Water Manag. 187, 88–98. https://doi.org/10.1016/j.agwat.2017.03.017.

Wang, Y., Guo, Q., Xu, Y., et al., 2022. Optimizing urea deep placement to rainfall can maximize crop water-nitrogen productivity and decrease nitrate leaching in winter wheat. Agric. Water Manag. 274, 107971. https://doi.org/10.1016/J.AGWAT.2022.107971.

Wei, W., Yan, Y., Cao, J., et al., 2016. Effects of combined application of organic amendments and fertilizers on crop yield and soil organic matter: an integrated analysis of long-term experiments. Agric. Ecosyst. Environ. 225, 86–92. https://doi.org/10.1016/J.AGEE.2016.04.004.

Wibberley, E.J., 2006. Fertilising small-grain cereals for sustainable yield and high quality. IPI Bull No17 177.