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DOCTORATE THESIS

THEME:

EFFECT OF MANAGEMENT FACTORS AND CLIMATE CHANGE ON MIXED CROP-LIVESTOCK SYSTEMS IN THE SUDAN SAVANNA OF BURKINA FASO AND GHANA

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A THESIS

IN THE RURAL POLYTECHNIC INSTITUTE OF TRAINING AND APPLIED RESEARCH IN PARTNERSHIP WITH THE WEST AFRICAN SCIENCE SERVICE CENTRE ON CLIMATE CHANGE AND ADAPTED LAND USE (WASCAL), SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN CLIMATE CHANGE AND AGRICULTURE OF THE UNIVERSITY OF SCIENCES, TECHNIQUES AND TECHNOLOGIES OF BAMAKO (USTTB)

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EFFECT OF MANAGEMENT FACTORS AND CLIMATE CHANGE ON MIXED CROP-LIVESTOCK SYSTEMS IN THE SUDAN SAVANNA OF BURKINA FASO AND GHANA

Albert BERDJOUR

MASTER OF PHILOSOPHY (MPhil.): CROP SCIENCE

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JUNE 2025

Declaration

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This dissertation/thesis is the outcome of my own research and that neither a part nor whole of it has been presented for another degree in this university or elsewhere.

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I certify that this work was carried out by Albert Berdjour under my supervision and in accordance with the guidelines on supervision of dissertation/thesis laid down by the University of Sciences, Techniques and Technologies of Bamako.

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Table of Contents

Dedication

I dedicate this thesis to the Almighty God for HIS faithfulness, to my family for laying the foundation and to my friends, especially the "Table of Men" family for their support, motivation, and prayers.

Acknowledgement

These last four years of my PhD have been a challenging but great journey. I would like to thank the Almighty God for his faithfulness, blessings, guidance, favours, wisdom and protection throughout these years.

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Finally, I say kudos, and may God bless you all.

List of Acronyms

ADG	Average Daily Gain
AgERA5	Agricultural Earth Observation and Reanalysis for Climate and Land Applications, Version 5
ANOVA	Analysis of Variance
APSIM	Agricultural Production Systems Simulator
BCa	Bias-corrected and accelerated bootstrapping
BNU-ESM	Beijing Normal University Earth System Model
BQ	Bias Quantity
CanESM2	Canadian Earth System Model, 2nd generation
CEC	Cation Exchange Capacity
CH_4	Methane
CI	Confidence Interval
CO_2	Carbon Dioxide
CST	Conservational Tillage
CSV	Comma-Separated Values
CNT	Conventional Tillage
DBF	Database File
DSSAT	Decision Support System for Agrotechnology Transfer
DyNoFlo	Dynamic North Florida Diary Farm Model
EC	Electrical Conductivity
ECMWF	European Centre for Medium-Range Weather Forecasts
FAO	Food and Agricultural Organization
GCM	Global Circulation Model
GECROS	Genotype-by-Environment interaction on CROp growth Simulator
GFDL-ESM-2M	GFDL-ESM-2M stands for Geophysical Fluid Dynamics Laboratory Earth System Model, Version 2M

GHG	Greenhouse Gas
GPS	Geographical Positioning System
HPC	High Performance Computing
HROM	Household Resource Use Optimization Model
ICLS	Integrated Crop-Livestock System
IPCC	Intergovernmental Panel on Climate Change
IMPACT	Integrated Modelling Platform for Mixed Animal Crop Systems
ISRIC-WISE	International Soil Reference and Information Centre - World Inventory of Soil Emission Potentials
JRC	Joint Research Centre
JSON	JavaScript Object Notation.
LINTUL	Light Interception and Utilization
MCLS	Mixed Crop-Livestock System
MIDAS	Model of an Integrated Dryland Agricultural System
MPI-ESM-MR	Max Planck Institute Earth System Model Medium Resolution
MR	Mean Residual Error
MSE	Mean Squared Error
N_2O	Nitrous Oxide
NetCDF	Network Common Data Form
pH	Potential of Hydrogen
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCP	Representative Concentration Pathway
RF	Random forest
RMSE	Root Mean Squared Error
RR	Response Ratio
SIMPLACE	Scientific Impact assessment and Modelling Platform for Advanced Crop and Ecosystem management

SQL	Structured Query Language
SRNS	Small Ruminant Nutrition System
SSA	Sub-Saharan Africa
SSP	Shared Socioeconomic Pathways
SSPf	Single Super Phosphate
SUCROS	Simple and Universal CROp growth Simulator
TEB	Total Exchangeable Bases
TNT2	Topmodel-based Nitrogen Transfer and Transformation
Tmax	Maximum Temperature
Tmin	Minimum Temperature
TSP	Triple Super Phosphate
UAN	Urea Ammonium Nitrate
URL	Uniform Resource Locator
WA	West Africa
XML	eXtensible Markup Language

List of Tables

List of Figures

Résumé

Les systèmes agricoles diversifiés intégrant l'agriculture et l'élevage sont vulnérables au changement climatique et nécessitent des stratégies d'adaptation pour améliorer leur productivité. L'objectif principal de cette étude était d'évaluer l'effet du changement climatique sur la productivité des systèmes mixtes de culture et d'élevage (MCLS) dans la savane soudanaise d'Afrique de l'Ouest. L'étude, par le biais d'une revue systématique et d'une méta-analyse, a cherché à déterminer la contribution des systèmes mixtes culture-élevage à l'émission de gaz à effet de serre (GES) par le sol. Elle a également quantifié l'effet des pratiques d'application d'engrais sur les rendements en céréales et en légumes des MCLS au Ghana et au Burkina Faso en utilisant des informations détaillées sur les pratiques de gestion des engrais et les rendements qui ont été collectées auprès de 317 fermes MCLS réparties dans trois (3) districts/provinces de la région du Haut-Est du Ghana (Kassena Nankana, Builsa North, et Bongo) et sur le Plateau central du Burkina Faso (Loumbila, Ziniaré, et Zitenga), résumant respectivement les données sur leurs rendements en céréales et en légumes sous (1) les principales sources d'engrais, (2) le taux d'engrais N (kg ha-1), (3) le calendrier d'application de l'engrais et (4) les méthodes de placement de l'engrais. Le cadre de modélisation SIMPLACE a également été utilisé pour simuler la production des fermes MCLS typiques. L'application d'un tel cadre nous a permis d'estimer l'effet du changement climatique futur sur le rendement des cultures (maïs, mil, sorgho et arachide) et sur le nombre de têtes de bétail au Ghana et au Burkina Faso. Les résultats de la méta-analyse ont montré que les variables modératrices telles que la classe de drainage, la densité de peuplement, le climat, la quantité d'engrais N, le type d'engrais et la texture du sol exercent un contrôle plus important sur les émissions de gaz à effet de serre dans les MCLS. De même, les résultats ont montré que la source d'engrais et les taux d'azote recommandés spécifiques au pays ont augmenté ($P < 0,05$) les rendements de la plupart des cultures céréalières au Burkina Faso et au Ghana, et de toutes les cultures maraîchères au Ghana. D'autre part, le modèle SIMPLACE a été calibré et validé pour la prédiction du rendement en grain du MCLS. La quantité de biais, l'erreur résiduelle moyenne et l'erreur quadratique moyenne ont été utilisées pour déterminer la concordance entre le rendement céréalier observé et le rendement céréalier simulé par le modèle. L'évaluation du modèle indique que les rendements du maïs et du sorgho ont été légèrement et modérément surestimés, respectivement. Inversement, les rendements en grains du mil et de l'arachide ont été modérément sous-estimés. Dans l'ensemble, l'erreur résiduelle moyenne (ERM) se situe entre -12% et 18%, ce qui est jugé satisfaisant. Pour les effectifs de bétail, le modèle s'est écarté des valeurs observées en enregistrant une RM de 27 %. En outre, le modèle validé a été utilisé pour estimer les rendements céréaliers et les effectifs du bétail pour le passé (2000-2024) et projeter leurs changements futurs en utilisant les projections du modèle de circulation globale (MCG) à échelle réduite (2025-2050). Les résultats démontrent qu'à l'avenir, la région étudiée connaîtra probablement un déclin significatif du maïs (jusqu'à -34%), du mil (jusqu'à -57%), du sorgho (jusqu'à -53%), de l'arachide (jusqu'à -23%), et une augmentation significative du nombre de têtes de bétail (jusqu'à 181%).

Mots clés : émissions de GES du sol, gestion des engrais, SIMPLACE, bétail, rendement grain

Abstract

Diversified farming systems integrating crop and livestock operations are vulnerable to climate change and need adaptation strategies to improve the system's productivity. The main objective of this study was to assess the effect of climate change on the mixed crop-livestock systems (MCLS) productivity in the Sudan Savannah of West Africa. A systematic review and meta-analysis were first conducted to determine the contribution of MCLS to soil greenhouse gas (GHG) emissions. The effect of fertilizer application practices on grain and vegetable yields of MCLS in Ghana and Burkina Faso was also quantify using detailed information on fertilizer management practices and yield collected from 317 MCLS farms distributed across three (3) districts/provinces in the Upper East region of Ghana (Kassena Nankana, Builsa North, and Bongo) and over the Plateau central of Burkina Faso (Loumbila, Ziniaré, and Zitenga). Data was summarized, based on their grain and vegetable yields under (1) major fertilizer sources, (2) N fertilizer rate (kg ha^{-1}), (3) fertilizer application timing, and (4) fertilizer placement methods. The SIMPLACE modelling framework was also used to simulate the output of typical MCLS farms. Applying such a framework allowed us to estimate the effect of future climate change on crop (maize, millet, sorghum, and peanut) yield and livestock numbers in the selected locations in Ghana and Burkina Faso. The findings of the meta-analysis showed that moderating variables such as drainage class, stocking density, climate, N fertilizer amount, fertilizer type, and soil texture exerted greater control over the GHG emissions in MCLS. Similarly, results showed that fertilizer source and country-specific recommended N fertilizer rates significantly increased ($P < 0.05$) yields of most grain crops in both Burkina Faso and Ghana, and all vegetable crops in Ghana. On the other hand, the SIMPLACE model was calibrated and validated for grain yield prediction of MCLS. Bias quantity, mean residual error and root mean squared error was used to determine the agreement between observed and model-simulated grain yield. Model evaluation indicated that maize and sorghum yields were slightly and moderately overestimated, respectively. Conversely, grain yields of millet and peanut were moderately underestimated. Overall the mean residual error (MR) was between -12% to 18% which was judged satisfactorily. For livestock numbers, the model deviated from observed values by recording an MR of 27%. Furthermore, the validated model was used to estimate grain yields and livestock numbers for the past (2000-2024) and project their future changes using downscaled Global Circulation Model (GCM) projections (2025–2050). The results demonstrated that in the future, the study locations will likely experience a significant decline in maize (up to -34%), millet

(up to -57%), sorghum (up to -53%), peanut (up to -23%), and a significant increase in livestock numbers (up to 181%).

Keywords: soil GHG emission, fertilizer management, SIMPLACE, livestock, grain yield

CHAPTER ONE: INTRODUCTION

1.1 Problem statement and justification

Sustainable intensification of agriculture aims to increase resource-use efficiency and limit the expansion of the agricultural land area in part by leveraging ecosystem services (e.g., soil fertility, nutrient cycling, grassland restoration) and harnessing ecosystem resilience mechanisms such as soil carbon accrual (Sanderson et al., 2013). Walker (2020) refers to resilience as the ability of an agricultural system to cope with climate variability and change, and it is rooted in the principle of exposure, sensitivity, and adaptive capacity.

One concept that expands and is consistent with a sustainable and resilient ecosystem; whether biological, temporal, or spatial – is the diversification of agricultural systems through mixed crop-livestock systems (MCLS). Sere and Steinfield (1996) defined MCLS as those in which at least 10% of the feed comes from crops and/or crop-by-products or more than 10% of the total agricultural production comes from non-livestock farming activities. MCLS have been shown to improve productivity per unit of land area and labour (Ghahramani & Moore, 2016), shifts in soil biological, physical and chemical properties (de Carvalho et al., 2018; Rahman et al., 2019), water and nutrient cycling (Martins et al., 2016) and plant-soil interactions (Rahman et al., 2019). Mixed crop-livestock systems are also reported to enhance climate change resilience through buffering mechanisms in both field-level biophysical processes, e.g., nutrient cycling (Szymczak et al., 2020) or improved crop productivity (Tracy & Zhang, 2008), and farm-level socioeconomics, e.g., economic risk mitigation and livelihood diversification (Bell et al., 2014). Similarly, it is estimated that 69% of global milk production and 61% of global ruminant meat production are sourced from crop-livestock mixed systems (Ghahramani & Moore, 2016).

If global warming continues at the current trajectory, the global average temperature is likely to increase by 1.5 °C by 2050 compared to pre-industrial levels (Thornton et al., 2014). A higher and faster temperature increase of 2 °C has even been projected for Africa. Similarly, many projections on West Africa's future climate indicate adverse impacts that are likely to lead to productivity crises unless sustainable solutions are in place. The Intergovernmental Panel on Climate Change (IPCC) estimates that crop-growing periods in West Africa may shorten by an average of 20% by 2050, causing a 40% decline in cereal yields and a reduction in cereal biomass for livestock (IPCC, 2022). This is attributed to the projected 5% decline in rainfall and frequently long-lasting and intense droughts which are likely to increase the area of arid and semiarid land by 5–8% by 2050 (IPCC, 2022). Similarly, changes in the availability and quality of forage resources, access to water, species and breeds of livestock that can be kept, livestock mobility, and animal diseases are specific impacts of climate change on livestock being reported for West Africa (Zougmoré et al., 2016). The four Global Climate Models (GCMs) used by Jalloh et al. (2013) all projected a temperature rise from 1.5 to 2.3 °C between 2000 and 2050, while changes in mean annual rainfall ranged from a drop of 23 mm per year to a rise of 22 mm per year. These projected changes are expected to cause adverse impacts West Africa, a region that produces at least 30% of the food requirements (crop and livestock) of the African continent.

Adapting crop and livestock production systems (mixed or specialized) to the changing climate is of great importance in the Sub-region. However, despite the fact that many smallholder farming systems in West Africa involve the interactions of crop and livestock systems, the modelling of climate impact on the mixed system using combinations of detailed crop and livestock models is comparatively under-developed (Thornton & Herrero, 2001). A similar observation was reported by Ghahramani and Moore (2016), who found that, crop-livestock modelling studies, conducted in the Sudan Savanna zone of West Africa were uncommon. One of the few studies was from Rigolot et al. (2017) who examined the impact of climate change on smallholder crop-livestock systems in Burkina Faso. While specific impacts of climate change have been reported for crops (Defrance et al., 2020; Roudier et al., 2011; Sultan et al., 2019) and livestock (Niggol et al. 2007; Zougmoré et al. 2016) in West Africa, it is uncertain how future conditions will impact mixed crop-livestock systems, especially in the Sudan Savannah zone of West Africa given the data scarcity on this agricultural system (Ghahramani & Moore, 2016; Thornton & Herrero, 2001). As for all modelling activities, the most efficient way to proceed depends on the nature of the systems under study and the precise questions that must be addressed (Thornton & Herrero, 2001). In this study, we will use an existing integrated crop-livestock model, under the SIMPLACE (Scientific Impact assessment and Modelling Platform for Advanced Crop and Ecosystem management) modelling framework, a process-based simulation tool to understand the potential effect of climate change on crop-livestock farming systems in the Sudan Savannah zone of West Africa. To achieve this, the model was calibrated and validated based on observations and further applied to explore the impact of climate change based on future climate projections from the Global Climate Model (GCM) GFDL-ESM4: Geophysical Fluid Science Laboratory-Earth System Modelling (https://www.gfdl.noaa.gov/earth-system-esm4/), for future climate scenarios in (2025-2050) relative to a historical baseline of 2000-2024.

1.2 State of the knowledge

1.2.1 Environmental and management factors affecting greenhouse gas fluxes from soils in mixed crop-livestock systems

Mixed crop-livestock systems (MCLS) present a viable method for sustainably intensifying agricultural practices (Kumar et al., 2019). These systems contribute to the production of diverse and nutritious food while supporting rural economies and minimizing further environmental degradation (HLPE, 2019). MCLS have gained renewed interest as they are crucial to ecological intensification strategies, which aim to reduce reliance on synthetic inputs by leveraging ecosystem services (Bommarco et al., 2013). However, the inherent spatial and temporal complexities of MCLS (Franzluebbers et al., 2014) necessitate comprehensive, interdisciplinary evaluations to develop effective management guidelines (Ghimire et al., 2013; Liebig et al., 2020).

Management practices, such as crop selection and cropping systems, significantly impact greenhouse gas (GHG) emissions by influencing the quality and quantity of crop residues returned to the soil (Sainju et al., 2008). Nitrogen fertilization generally enhances N_2O emissions (Dusenbury et al., 2008; Mosier et al., 2006) but has variable effects on CO_2 and CH_4 emissions. The application of manure and urine to soil can also contribute to GHG emissions. Additionally, environmental factors like soil type and climate can determine whether a farming system acts as a source or sink for GHGs (Peterson et al., 2020). Cavigelli et al. (2012) highlighted the importance of evaluating the mitigation potential of agricultural systems like MCLS in reducing GHG emissions. Despite this, limited research has explored the capacity of MCLS to achieve this goal. Thus, it is crucial to assess how environmental factors and management decisions influence GHG fluxes in MCLS.

1.2.2 The impact of fertilizer application on grain and vegetable yield in mixed crop-livestock systems

Smallholder farmers in Sub-Saharan Africa predominantly engage in subsistence farming, which is characterized by limited productivity, nutrient depletion, and dependency on rain-fed agriculture (Akinseye et al., 2024; Lal et al., 2015). These farmers are also increasingly facing the challenges of a warming climate, which has been linked to negative impacts on crop yields in the region (Lal et al., 2015; Nyoni et al., 2024; Srivastava et al., 2012). To address these challenges, enhancing food production through improved agricultural practices is critical. Fertilization has emerged as a viable strategy for boosting crop productivity (Cai et al., 2019; Liu et al., 2021). However, fertilization practices must minimize negative environmental impacts while maintaining or improving soil quality (Lal et al., 2015).

A widely accepted framework for sustainable fertilization is the "4R" principle, which advocates for using the right nutrient source, applying it at the right time, with the right method, and at the right rate. Mixed crop-livestock systems (MCLS) are increasingly being proposed as an alternative to reverse soil fertility decline and reduce environmental degradation while enhancing crop yields (Da Silveira Bueno et al., 2021; Peterson et al., 2020; Rahman et al., 2019). Despite their potential, limited research has been conducted in real-world settings, particularly among small-scale farmers, necessitating a more comprehensive evaluation of fertilizer management practices within the context of MCLS in Sudan-Savannah of West Africa.

1.2.3 The use of process-based models to simulate mixed crop-livestock systems

The interactions between crops, livestock, and agroecosystems are complex and multifaceted (Parsons et al., 2011). Given this complexity, mathematical models have become increasingly essential for quantifying and understanding these systems. They are critical for supporting decision-making, optimizing resource use, and developing adaptation strategies, particularly in response to challenges like climate change (Wallach et al., 2018). Simulation modelling offers a valuable framework for analyzing crop-livestock systems, as highlighted by Masikati et al. (2017), with the potential to achieve environmental, economic, and social objectives that field experiments or participatory approaches might struggle to address.

Thornton and Herrero (2001) emphasized that due to the intricate interactions within these systems, modelling can provide a feasible approach to assess the impacts of various interventions or changes. However, the model application is often constrained by a lack of comprehensive data (both biophysical and socioeconomic) and validated modelling tools. Moreover, while few integrated assessment tools exist, existing models can be coupled to provide useful insights (Masikati et al., 2017). Bationo et al. (2012) also noted that expanding the use of these tools, especially in the African context, could significantly improve our understanding of interventions to optimize crop-livestock productivity with fewer resources, compared to traditional field experiments. Therefore, for a comprehensive evaluation of crop-livestock systems, it is crucial to develop or employ modelling frameworks that can integrate and analyze the trade-offs and synergies within these systems at various scales.

1.2.4 Assessing the potential effect of the projected climate change on mixed crop-livestock productivity

The global population is projected to reach approximately 9.55 billion by 2050, with much of this growth anticipated in developing countries (Alexandratos & Bruinsma, 2012). In Sub-Saharan Africa, smallholder mixed crop-livestock systems (MCLS) are expected to play a crucial role in ensuring food security (Rigolot et al., 2017). However, the ability of these systems to meet increasing food demands must be assessed in the context of a changing climate (Thornton & Herrero, 2015). Despite the significance of MCLS, there is limited knowledge regarding the specific impacts of climate change on such systems in Sub-Saharan Africa (Escarcha et al., 2018; Rigolot et al., 2017; Thornton et al., 2014). One challenge lies in the fact that much of the research tends to focus on isolated components of the system (Zougmoré et al., 2016). Moreover, discussions on the effects of climate change on MCLS, particularly in Sub-Saharan Africa are often framed in general, qualitative terms (e.g., Thornton et al. 2014; Thornton and Herrero 2015), while studies that provide quantitative assessments remain scarce. To accurately assess the potential impact of climate change on MCLS, a systems-level approach at the farm scale is essential, one that incorporates the interactions between different farm components and processes at various scales (Descheemaeker et al., 2016). Without well-quantified assessments of climate risks, there is a significant risk of either overestimating or underestimating the true impacts of climate change on MCLS (Thornton et al., 2014).

1.3 Research hypothesis

I. Nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) emissions from soils under MCLS will not be affected by environmental and management factors.

II. Grain and vegetable yields will not be influenced by fertilizer application practices in MCLS.

III. The SIMPLACE model when calibrated with empirical farm data is capable of actually simulating the annual output of different crop-livestock farms under varying weather conditions.

IV. The expected future climate conditions will not cause a difference in the output of individual crop-livestock farms in the Sub-humid Savannah of Burkina Faso and Ghana.

1.4 Objectives

1.4.1 Overall objective

The overall objective of this research was to assess the productivity of mixed crop-livestock farms in the Sudan Savannah of Burkina Faso and Ghana through survey studies, model simulations and climate scenario analysis.

1.4.2 Specific objectives

I. Determine the response patterns of nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) emissions in MCLS across diverse environments and management scenarios.

II. Quantify the potential impact of current fertilizer application practices on grain and vegetable yields in smallholder MCLS of Ghana and Burkina Faso.

III. Validate the SIMPLACE model, to simulate the output of typical crop-livestock farms based on actual data collected at farm scale.

IV. Apply the validated model for the estimation of climate change impacts on mixed-crop livestock production system at farm scale in the Sub-humid savannah of Burkina Faso and Ghana.

CHAPTER TWO: LITERATURE REVIEW

2.1 Sudan savanna zone of West Africa

The Sudan Savanna is a semi-arid transitional zone located between Africa's arid Sahel region and the more humid tropical Guinea zone. Stretching from the Atlantic Ocean in the West to the Indian Ocean in the east (TerrAfrica, 2011), this ecosystem encompasses several West African countries, including Benin, Burkina Faso, Ghana, Mali, Mauritania, Niger, Nigeria, Senegal, and Togo. Agriculture forms the backbone of the economy in this region, providing livelihoods for the majority of its residents (Callo-Concha et al., 2013). However, despite its agricultural potential, various abiotic and biotic challenges hinder the region's productivity. Key limiting factors include irregular water availability due to erratic rainfall and frequent droughts (Boansi et al., 2019), declining soil fertility (MacCarthy et al., 2018), and the slow adoption of improved farming practices.

2.1.1 Climate of the Sudan Savannah of West Africa

The climate of the Sudan Savannah is primarily influenced by the West African Monsoon (WAM) system (Nicholson et al., 2013). Annual precipitation in the region typically ranges between 600 and 900 mm (Callo-Concha et al., 2013; Ker, 1995), with much of the rainfall generated by mesoscale convective systems (Bliefernicht et al., 2018). This rainfall is characterized by significant spatiotemporal variability, particularly at smaller scales, which presents challenges for rain-fed agriculture (Bliefernicht et al., 2018). According to OSS (2019), annual rainfall in this zone decreased by an average of 20-40% between 1931–1960 and 1968–1990, compared to a 15% reduction in the tropical rainforest regions. This decline has led to the southward movement of isohyets by approximately 150-200 km (OSS, 2019) . Since the mid-1990s, there has been a partial recovery in rainfall levels, although this improvement does not necessarily indicate a full "regreening" of the region or a return to previous environmental conditions (Dardel, 2014).

2.1.2 Climate projections for the Sudan Savannah zone of West Africa

2.1.2.1 Precipitation

Rainfall projections for West Africa indicate a precipitation gradient, with reductions in the west and increases in the east (Dosio et al., 2021; Ranasinghe et al., 2021). This pattern is observed even at 1.5 °C of global warming, with the intensity of these changes increasing at higher warming scenarios (Sylla et al., 2018). At 2 °C of warming, projections suggest a drier, more drought-prone climate in West Africa, particularly towards the end of the 21st century (Sylla et al., 2016). Meteorological droughts in West Africa are expected to lengthen from around 2 months (1980–2014) to about 4 months during 2050–2100 under Representative Concentration Pathways (RCP) 8.5 and SSP5-8.5 (Ukkola et al., 2020).

Despite models predicting overall decreased rainfall across West Africa, the Sudan savanna is projected to face the most severe droughts in the coming decades (Ayanlade et al., 2022). These precipitation shifts are likely to cause significant changes in West Africa's agro-ecological zones (high confidence). OSS (2019) noted a southward shift of isohyets by 150–200 km in this region. However, climate projections carry uncertainties, influenced by different General Circulation Models (GCMs) used in Climate Model Intercomparison Projects (CMIP) (Christensen et al., 2013). While GCMs largely agree on broader trends, there is significant variability among them (Zappa & Shepherd, 2017). For example, under RCP4.5 and RCP8.5 scenarios from the GFDL-ESM-2M model, Danso (2015) projected rainfall increases of 40%, 44%, and 47% in three Sudan savanna locations (Dano, Vea, and Dassari) by 2050. Conversely, ensemble mean projections from the Beijing Normal University Earth System Model (BNU-ESM), Canadian Earth System Model (CanESM2), and Max Planck Institute Earth System Model (MPI-ESM-MR) under RCPs 2.6, 4.5, and 8.5 suggest rainfall reductions of 2%, 4%, and 1% in the dry savannas of northern Benin (Amouzou et al., 2019). Khelifa et al. (2021) attributed uncertainties in rainfall projections to rising temperatures and potential evapotranspiration. However, Klutse et al. (2016) found that ensemble mean computations significantly reduce the variability among individual model predictions.

2.1.2.2 Temperature

The increasing temperatures and their potential impacts on climate change in West Africa have been highlighted by numerous studies (Arfasa et al., 2024; Defrance et al., 2020; W. Sawadogo et al., 2024; Zougmoré et al., 2016). At global warming levels of 1.5 °C, 2 °C, and 3 °C above pre-industrial levels, West Africa’s mean annual temperatures are projected to rise by approximately 0.6 °C, 1.1 °C, and 2.1 °C, respectively, compared to the 1994–2005 baseline (Trisos et al., 2022). The number of hot days per year is also expected to increase across all warming scenarios, with more significant rises at higher warming levels (Trisos et al., 2022).

Using ensemble mean predictions from models such as BNU-ESM, CanESM2, and MPI-ESM-MR, Amouzou et al. (2019) forecasted rising minimum temperatures of +1.0 °C (RCP 2.6), +2.0

°C (RCP 4.5), and +4.7 °C (RCP 8.5), along with maximum temperature increases of +1.1 °C (RCP 2.6), +2.0 °C (RCP 4.5), and +4.6 °C (RCP 8.5) for the dry savanna in northern Benin, West Africa. Similarly, projections for the Vea catchment in Ghana suggest temperature increases of 2.1–3.5 °C under SSP4.5 and 2.7–4.15 °C under SSP8.5 (Arfasa et al., 2024). In the Sudan-Sahel region of Burkina Faso, temperatures could rise by over 4.3 °C by the end of the century under SSP8.5. Crucially, climate models predict more frequent dry spells in the Sudan savanna zone (Danso, 2015), likely leading to increasingly arid conditions that threaten livelihoods and food security. Callo-Concha et al. (2013) suggested that the combination of high temperatures and degraded soils in this region may be key factors contributing to poor soil fertility, a major limitation to improving crop productivity under changing climate conditions.

2.1.3 Soil

The soils of the Sudanian zone of West Africa are formed on Paleoproterozoic granitoid bedrock, with variations in Neoproterozoic and Cenozoic layers depending on location (Sandwidi, 2007). The landscape is predominantly flat to gently undulating, with slight depressions that form dry valley, and is characterized by ferralitic soils known for their stable microstructure and excellent initial drainage properties (OSS, 2019). Hilltops are often capped with iron, featuring shallow, sandy soils that are well-drained, and in some areas, rock outcrops are present. These soils transition to yellow-brown clay on the mid-slopes. Nitrogen and phosphorus are the primary nutrients limiting agricultural productivity (Dibabe, 2000; Mitchell et al., 1979; Sanchez, 1976). Although the total phosphorus content can be relatively high, soils with clayey subsoils or iron mottles tend to have low levels of plant-available phosphorus. In contrast, potassium (K) is generally not a limiting nutrient in soils derived from granitic parent materials (Nye & Greenland, 1960). The cation exchange capacity (CEC) is typically low, around 4 meq 100 g^{-1}, and base saturation is generally above 35%. However, soils in this region tend to acidify under intensive cultivation (Sanchez, 1976). This issue is exacerbated by the fact that 40% of agricultural land is currently affected by human-induced degradation (Zougmoré, 2003).

2.1.4 Farming system in Sudan Savannah zone of West Africa

In the semi-arid Sudanian regions of West Africa, agro-pastoral systems dominate the landscape, where livelihoods are largely dependent on crops, livestock, and off-farm employment (Callo-Concha et al., 2013; Robinson et al., 2011). Historically, shifting cultivation through fallow systems is widespread in the Sudan Savanna (Andriesse & Fresco, 1991). These fallows were essential for replenishing soil fertility after periods of continuous cropping (Callo-Concha et al., 2013). However, increasing pressure on land and natural resources has led to a reduction in fallow periods, resulting in the loss of woody species, declining soil fertility, and expansion of cropping into marginal lands (De Ridder et al., 2004; Sanchez, 1976).

De Ridder et al. (2004) noted that while continuous cropping can lead to soil fertility depletion, the rate of decline is variable and may not be immediately apparent. This variability is influenced by farmers' cropping choices and the spatial management of their farms. For example, Prudencio (1993) highlighted that farm layout often follows a concentric pattern, with three land types: compound land, family land, and bush-land. Compound land, close to the homestead, benefits from organic inputs like household waste and manure, resulting in higher fertility and more intensive cropping. Evidence from Burkina Faso suggests that continuous cropping can even improve certain soil fertility indicators compared to long-term fallow on compound land (Prudencio, 1993). Family land often employs intercropping with fewer manure applications, while bush-land, used primarily for grazing, still incorporates fallow practices (Bationo et al., 1996; Ouédraogo, 2004; Prudencio, 1993). Average farm sizes in these systems are generally small, with most farmers focusing on subsistence crop production. For instance, in Ghana’s Upper East Region, the average farm size is just 0.6 hectares, and 87% of farmers manage less than 1 hectare (Amanor-Boadu et al., 2015).

The integration of crops and livestock is common in these systems, providing benefits such as supplemental income and food security. Key crops include maize (*Zea mays*), sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), rice (*Oryza sativa*), peanuts (*Arachis hypogaea*), and cowpea (*Vigna unguiculata*) (Powell, 2014). However, yields are often low due to factors such as climate variability, limited use of external inputs like fertilizers, and labour shortages (Bjornlund et al., 2020; Ntare et al., 2008; Schindler, 2009). The cropping calendar typically starts in May or June, driven by rainfall distribution and the availability of organic matter (manure, compost), which also significantly influences yields (Callo-Concha et al., 2013). In Burkina Faso, yield variability from 1961 to 2020 is closely linked to fluctuating rainfall patterns (Sanou et al., 2023), a trend also observed in Ghana's Sudan Savanna (Adimassu et al., 2023). Low fertilizer use further contributes to soil fertility depletion, often described as "soil mining," where nutrients are extracted faster than they are replenished (Leitner et al., 2020; ten Berge et al., 2019). To counteract this, integrating livestock with crops has proven beneficial for nutrient cycling, improving farm productivity, and enhancing resilience to climate variability (Bell et al., 2014; Peterson et al., 2020; Szymczak et al., 2020).

2.2 Mixed Crop-Livestock systems

Sere and Steinfield (1996) defined mixed crop-livestock systems (MCLS) as those in which at least 10% of the feed comes from crops and/or crop-by-products or more than 10% of the total agricultural production comes from non-livestock farming activities. This system integrates crop and livestock production to leverage the benefits of interactions between the two (Ryschawy et al., 2012). The goal of combining these activities is to create resources that can be strategically applied to improve the efficiency, productivity, and sustainability of the integrated farming system (Afi & Parsons, 2023). MCLS have been shown to improve productivity per unit of land area and labour (Ghahramani & Moore, 2016), shifts in soil biological, physical, and chemical properties (de F. Carvalho et al., 2018; Rahman, Larbi, et al., 2019), water and nutrient cycling (Martins et al., 2016) and plant-soil interactions (Rahman, Larbi, et al., 2019). Crop-livestock mixed systems are also reported to enhance climate change resilience through buffering mechanisms in both field-level biophysical processes, e.g., nutrient cycling (Szymczak et al., 2020) or improved crop productivity (Tracy & Zhang, 2008), and farm-level socioeconomics, e.g., economic risk mitigation and livelihood diversification (Bell et al., 2014). Similarly, it is estimated that 69% of global milk production and 61% of global ruminant meat production are sourced from crop-livestock mixed systems (Ghahramani & Moore, 2016).

The adoption of integrated crop-livestock farming can also present challenges, including competition for natural resources and potential environmental impacts. Excessive vegetation removal through grazing or fodder harvesting, along with soil tillage by animal traction, can lead to environmental degradation (Williams et al., 1999). Furthermore, integrated crop-livestock systems may impact property rights, equity, and risk management within farming communities (Williams et al., 1999). Competition for land due to population growth, agricultural expansion, and grazing requirements may hinder farmers from realizing the full benefits of mixed crop-livestock systems. For example, in sub-Saharan Africa (SSA), smallholder farmers in crop-livestock systems often contend with fragmented landholdings, seasonal climate variability, reliance on family labor, and limited access to transportation and markets (Amejo et al., 2018). Addressing these issues requires technological innovations and agricultural policies tailored to the needs of smallholders in SSA, grounded in a thorough understanding of their production goals and the organizational structure of mixed crop-livestock systems (Amejo et al., 2018).

2.2.1 Typologies of MCLS

The integration of crops and livestock can be structured and organized at the field, farm, and territorial levels. At each of these levels, mixed crop-livestock systems (MCLS) display varying degrees of integration, which are associated with differing volumes of external inputs and outputs across both time and space.

2.2.1.1 Field-level integration

In this type of MCLS, crops and livestock share the same field at different times. Primarily, the field is used for crop production, including both annual and perennial forage, while livestock graze during the off-season or between crop rows, such as in orchards or vineyards (Hilimire, 2011). Peterson et al. (2020) described four types of MCLS within this integration level: (1) Forage Rotation – a multi-year cycle alternating annual crops with grazed forage crops (e.g., 3 years of grazed perennial ryegrass, 2 years of peanuts, and 1 year of corn); (2) Cover Cropping – an annual rotation of a main cash crop with a grazed, off-season cover or forage crop (e.g., summer soybean rotated annually with winter-grazed ryegrass); (3) Stubble Grazing – grazing livestock on crop residues left after harvest (e.g., grazing on corn stalks); (4) Dual-Purpose Crop – grazing an annual crop in its vegetative phase before it is harvested for grain (e.g., early-stage wheat grazed by sheep and then harvested for grain).

Integrating grazing animals into cropland fosters unique interactions among plants, soil, and livestock that distinguish this system from other integration types (Lemaire et al., 2014). This level of integration offers a higher degree of crop-livestock interaction, as most fodder for livestock is cultivated on cropland, which also receives all manure produced. However, intensive stocking rates and frequent grazing have been linked to soil compaction and partial degradation (Ambus et al., 2018; de Carvalho et al., 2010).

2.2.1.2 Farm-level integration

Crops and livestock are often spatially separated or maintained as small, independent enterprises within a farm (Hilimire, 2011; Peterson et al., 2020). According to Peterson et al. (2020), this configuration is frequently the default in smallholder systems, exemplified by the cut-and-carry method. In this system, crop residues are harvested for animal feed, while livestock manure is collected and used as a soil amendment. If livestock are housed in corrals, barns, or kraals, manure collection for field application becomes easier and can also be composted (Hilimire, 2011). Permanent pastures or communal grazing areas are typically allocated for supplementary feeding. In these systems, pastures or bushlands are large and generally located on steep hillsides, whereas arable and forage crops occupy more productive, irrigable, and well-drained land (Ryschawy et al., 2017).

At the farm level, integration is usually highest on smaller farms and declines as farm size increases. This trend is often due to constraints in transporting manure, crop residues, and livestock, along with competition for manure as an energy source, construction material, and fertilizer. Corralling, where animals are kept overnight on fallow fields during the off-season, is another form of farm-level integration that enables manure and urine deposition, enhancing soil fertility and minimizing labour requirements for manure handling, storage, and spreading, with nitrogen loss reductions of 40–60% (Defoer et al., 2000; Powell et al., 2004; Powell, 2014; Sangaré et al., 2002). Corralling has been shown to improve crop yields more effectively than manure gathered from stalls or kraals alone (Powell, 2014). According to Liniger et al. (2011), corralling one adult sheep or goat in a 4m² area for five nights can deposit approximately 1 kg of manure dry matter. It is worth noting that, depending on how the farmer manages the corralled land, this system can represent field or farm-level integration.

In Sub-Saharan Africa, farm-level integration is particularly prevalent (Peterson et al., 2021; Berdjour et al., 2024). Overall, key barriers to farm-level integration include a limited available workforce and a decline in the skills and knowledge required to optimize both crop and livestock systems (Asai et al., 2018; Martin et al., 2016).

2.2.1.3 Territory-level integration

MCLS can also operate at larger scales than individual farms through collaboration between specialized crop and livestock farms (Martin et al., 2016; Russelle et al., 2007). Territory-level integration seeks to connect these specialized farms to promote both diversification and sustainable management of resources, reducing the negative impacts of intensification, such as grassland loss due to intensified livestock production (Moraine et al., 2014). As cited by Asai et al. (2018), Entz et al. (2023), and Martin et al. (2016) described three main forms of territory integration based on the degree of spatial, temporal, and organizational coordination among farms. The first and simplest form is direct partnerships between crop and livestock farms, where they exchange raw materials like manure, grain, fodder, and straw. A second type involves local crop and livestock farmer groups negotiating land-use patterns collaboratively. The third and most extensive form functions on a regional level, with spatially separated groups of crop and livestock farms coordinated by a third-party entity, such as an agricultural cooperative, without necessarily requiring direct communication among all involved farmers.

Moraine et al. (2017) and Asai et al. (2018) identified spatial proximity as a key factor in enabling coordinated arrangements that foster stable and trusting relationships. Moreover, cooperation among specialized farms can open access to local resources that might otherwise remain unavailable or underutilized, such as land and livestock feed (Regan et al., 2017). Establishing direct, local markets could address the limitations of specialized supply chains, enhancing both economic outcomes (Moraine et al., 2017) and resource-use efficiency (Regan et al., 2017). However, organizational challenges can obstruct successful territory-level integration (Asai et al., 2018), as it requires coordination across multiple participants and balancing individual versus collective goals (Ryschawy et al., 2017). For example, at this level, crop choices on specialized farms may not always align with the fodder requirements of nearby livestock farms, and similarly, manure availability and quality may not fully meet crop fertilization needs.

2.3 Effect of MCLS on soil quality

Soil quality refers to the ability of soil to function within natural or managed ecosystem boundaries, supporting plant and animal productivity, maintaining or enhancing water and air quality, and contributing to human health and habitation (Karlen et al., 1997). Integrating crop and livestock systems (MCLS) offers opportunities to address challenges such as low and declining soil fertility, particularly for smallholder farmers. Studies have reported positive synergistic effects of MCLS on soil physical, chemical, and biological properties compared to monocropping systems (Lemaire et al., 2014; Rahman, Larbi, et al., 2019). However, the effects of MCLS on soil properties remain inconsistent and subject to debate. Variations in outcomes are likely influenced by management decisions, including crop type, livestock type, stocking density, and tillage methods.

2.3.1 Soil physical properties

Soil properties that enhance root growth, retain and supply water, hold and cycle nutrients, facilitate gas exchange, support biological activity, and store carbon are largely determined by soil physical attributes and processes (Schoenholtz et al., 2000). Unlike bulk density, which varies among soil types, attributes like soil texture and depth are relatively stable over time (Schoenholtz et al., 2000). Acosta-Martínez et al. (2004) reported significantly higher aggregate stability and bulk density in crop-livestock systems compared to continuous cotton systems. Similarly, comparisons of grazing and non-grazing management systems revealed higher macro-porosity in grazed areas following brachiaria and soybean cultivation (Bonetti et al., 2015). de Souza et al. (2010) suggested that grazing stimulates tillering and enhances root system development, which, according to Franzluebbers et al. (2012), improves soil structure, infiltration, aeration, and water retention. It is also known that the inclusion of multiple forages in MCLS, via their root systems significantly improves soil aggregate stability, macro-porosity, and hydraulic conductivity, which is particularly beneficial for highly fragile soils, such as sandy soils. In addition, their root growth can rearrange soil particles, favoring the flux of water and nutrients through better aggregation and connectivity of soil pores (Franzluebbers et al., 2011, Anghinoni et al., 2013). These effects are not only visible in the soil's uppermost layer, but also through the soil profile (Lanzanova et al., 2007).

Conversely, other studies highlight the negative impacts of livestock grazing on soil quality in MCLS. For instance, corralling sheep and goats at stocking densities of 70 and 140 head/ha increased soil bulk density and reduced porosity compared to non-corralled plots (Rahman, Larbi, et al., 2019). Similarly, Moreira (2014) observed adverse effects in post-grazing conditions, such as increased soil compaction and reduced pore space. High-intensity grazing systems were also associated with reduced soil porosity (Ambus et al., 2018). Cecagno et al. (2016) noted that even low levels of soil compaction can adversely affect the physical properties of subsurface soil layers.

Soil physical properties at a depth of 0–5 cm were significantly influenced by cattle grazing, particularly in pastures with sward heights of 10 cm and 20 cm (Bonetti et al., 2019). As a result, the water infiltration rate decreased by 81% following grazing and by 47% after the soybean harvest in pastures with a sward height of 10 cm, compared to ungrazed areas. However, assessments of physical properties conducted during single time periods may fail to capture the dynamic and intricate interactions within the soil-plant-animal matrix (Simões et al., 2023). This underscores the need for a comprehensive understanding of how management practices within MCLS influence soil quality across varying conditions and over time.

2.3.2 Soil chemical properties

Efficient nutrient utilization is a critical aspect of mixed crop-livestock systems (MCLS), enabling the simultaneous achievement of productivity and environmental sustainability by reconnecting carbon and nitrogen cycles (Soussana & Lemaire, 2014). Nutrient cycling facilitated by ruminant livestock can reduce reliance on synthetic fertilizers for crops (Powell et al., 1996). However, excessive nutrient accumulation from livestock manure on croplands poses risks to water quality (Schoumans et al., 2014). Consequently, optimizing nutrient distribution across time and space is essential for sustainable mixed crop-livestock systems (MCLS) (Hochman et al., 2013).

Despite the importance of chemical soil functions, distinguishing the chemical and biological indicators of soil quality can be challenging due to their interconnectedness (Schoenholtz et al., 2000). For instance, mineralizable nitrogen (N) has been categorized within both groups (Reganold & Palmer, 1995). As a result, Schoenholtz et al. (2000) highlighted critical soil chemical properties related to agricultural soil quality, such as soil organic carbon status (e.g., organic carbon (OC) and organic matter), nutrient availability (e.g., organic nitrogen, total phosphorus, cation exchange capacity (CEC)), soil acidity (pH), and salinity (electrical conductivity (EC)), as key indicators of nutrient-supplying capacity. To maintain sustainable MCLS, it is essential to understand how management practices influence these indicators in soils under these systems.

In their study of cover crop management within MCLS, Soussana & Lemaire (2014) found that intensive grazing by sheep reduced the carbon-to-nitrogen (C:N) ratio of cover crops, increasing soil inorganic N levels in areas where manure and urine were deposited. This process can disrupt the carbon and nitrogen cycles, potentially leading to N losses through nitrate leaching (Lazcano et al., 2022). Likewise, high grazing intensity in integrated crop-livestock systems (ICLS) has been shown to increase soil nitrogen losses compared to moderate and light grazing intensities, highlighting the need to determine the optimal grazing pressure for sustainable ICLS management (Assmann et al., 2014). Additionally, grazing on cover crops and winter forage crops was found to either increase or have no significant impact on near-surface total and labile phosphorus stocks in MCLS (da Silva et al., 2014; Liebig et al., 2012). Evaluating the effects of crop-livestock interactions on soil quality, Rahman et al. (2019) observed a significant increase in soil organic carbon in sheep and goat-corralling systems compared to non-corralling controls. Livestock urine contributes hydroxide ions during urea hydrolysis, enhancing soil pH, while also providing nutrients such as nitrogen and potassium. These findings align with earlier reports suggesting that MCLS improve soil pH, nitrogen, organic carbon, and potassium (Ikpe & Powell, 2002; Rahman, Larbi, et al., 2019).

Similarly, livestock grazing has been shown to enhance soil health by increasing soil carbon and organic matter content (Brewer & Gaudin, 2020). However, da Silva et al. (2014) noted that forage rotation within MCLS did not significantly affect total soil organic carbon and nitrogen but influenced soil acidity and exchangeable cations. Soil acidification, which serves as an indirect indicator of nutrient-use efficiency (Smith & Doran, 1997), was found to be less pronounced in treatments involving livestock, regardless of grazing intensity, compared to treatments without grazing. This reduced acidification is attributed to the higher retention of divalent cations, such as exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}), in grazed systems (da Silva et al., 2014; Martins et al., 2014). These findings highlight the nuanced effects of MCLS on soil properties, emphasizing the importance of tailored management practices to maximize soil health benefits.

2.3.3 Soil biological properties

Soil biological activity plays a vital role in restoring degraded soils, enhancing crop production, and supporting ecosystem services (Doran & Zeiss, 2000; Lehman et al., 2015). Spatial and temporal variations in environmental factors and management practices necessitate the development of agroecosystems that enhance the soil microbiome (Babin et al., 2019). Sekaran et al. (2021) noted that soil biological properties are highly sensitive to changes induced by management practices and ecological stress.

As a result, research by Chen et al. (2020) revealed that grazing management can influence soil microbial communities and their diversity either directly or indirectly. Through grazing activities, the deposition of manure, contributes to the functional capabilities of microbial communities, thereby improving soil health. Similarly, the incorporation of manure in soils under crop-livestock integration has been shown to increase soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and soil microbial quality (SMQ) (Rahman, Larbi, et al., 2019). The authors explained that feces and urine from grazing animals add organic matter to the soil, providing substrates for soil organisms and stimulating microbial activity. However, increased grazing intensity reduces soil carbon content, which, in turn, promotes bacterial diversity by decreasing the dominance of the phylum *Actinobacteria* while reducing fungal diversity by increasing the dominance of the fungal phylum *Ascomycota* (Eldridge et al., 2017; Sinha et al., 2024). Soil microbial biomass, actinomycetes, gram-positive bacteria, arbuscular mycorrhizal fungi (AMF), and overall fungal abundance were observed to be significantly higher in native Cerrado soils compared to monoculture pastures and MCLS (Sarto et al., 2020).

Similarly, grazing of forages disturbs the soil and affects the quantity and composition of soil organic carbon (SOC), altering microbial community structures and soil biochemical processes (Sandhu et al., 2019; Sekaran et al., 2019). The addition of feces and urine by grazing animals also modifies rhizosphere exudation patterns and botanical compositions (Clegg, 2006). Furthermore, crop rotations involving legumes and grasses, particularly when preceded by pasture in MCLS, have been shown to enhance total fungal and bacterial populations, actinobacteria abundance, and enzymatic activity (Sousa et al., 2020). Plant diversity also influences soil microbial communities by altering residue quality, increasing the quantity and diversity of exudates, and subsequently affecting microbial community composition and structure (Martucci do Couto et al., 2016).

2.4 Effect of MCLS on soil greenhouse gas (GHG) emissions

Agricultural practices are significant contributors to global greenhouse gas (GHG) emissions, including nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) (Barsotti et al., 2013; IPCC, 2014). Integrated farming systems, such as mixed crop-livestock, have been proposed as a sustainable alternative (de F. Carvalho et al., 2018; de Albuquerque Nunes et al., 2021). These systems offer mutualistic interactions between crops and livestock, potentially enhancing both agricultural productivity and environmental quality (Barsotti et al., 2013; de Moraes et al., 2014). However, the impact of MCLS on mitigating soil GHG emissions varies due to differences in system modalities, management practices, and environmental conditions. Therefore, given the growing significance of MCLS, it is crucial to evaluate how management strategies and environmental factors influence N_2O, CH_4, and CO_2 emissions from soils under MCLS compared to arable croplands or non-integrated systems.

2.4.1 Nitrous oxide (N_2O) emission from soils under MCLS

Nitrous oxide (N_2O) plays a critical role in both climate change and the depletion of stratospheric ozone (Wuebbles, 2009). It is primarily generated in soils through microbial processes, including nitrification (ammonia oxidation) and denitrification (nitrate reduction) (Torres et al., 2016). Numerous studies have identified key crop management factors such as fertilizer type, application rate and timing, crop type, and tillage practices as significant influencers of N_2O emissions.

Recognizing the influence of management practices on N_2O emissions in agricultural soils, Dieckow et al. (2015) reported that black oat (*Avena strigosa*) achieves high yields in mixed crop-livestock systems (MCLS) under moderate grazing and nitrogen (N) fertilization rates of 75–150 kg N ha^{-1}, with lower N_2O emissions compared to intensive grazing systems. Elevated N_2O emissions in intensively grazed systems were attributed to extended stocking periods, which increase nitrogen inputs to the soil via animal excreta (Assmann et al., 2015; Han et al., 2008). When soybean was integrated into MCLS, Nogueira et al. (2016) found an 80% increase in N_2O emissions compared to the pasture phase, possibly due to the combined effects of residual animal excreta in the pasture phase and nitrogen exudates released by soybean roots. Early sowing of ryegrass in soybean systems reduced N_2O emissions by 18.5% (821.3 vs. 1007.3 μg N_2O-N m^{-2} h^{-1}) compared to late sowing (Pilecco et al., 2019).

Past research highlights the variable impacts of management practices on N_2O emissions in MCLS, emphasizing the need for further research to clarify how management strategies and environmental conditions can reduce these emissions effectively. For example, continuous cropping systems under no-tillage management exhibited higher N_2O emissions compared to MCLS under similar conditions (Sato et al., 2017). Similarly, lower stocking rates (693 vs. 876 kg live weight ha^{-1}) in MCLS reduced N_2O emissions due to less animal trampling, which improved soil structure and increased total soil porosity (Amadori et al., 2022). Continuous corn systems, often relying on synthetic fertilizers, exhibited greater N_2O emissions compared to perennial grasslands (Christenson et al., 2021). On subtropical Ferralsols in Southern Brazil, cumulative N_2O emissions from MCLS were over three times higher than continuous cropping systems (4.3 vs. 1.3 kg N_2O-

N ha^{-1}), primarily due to nitrogen inputs and surface compaction (Piva et al., 2014). The role of fertilizer nitrogen in driving N_2O emissions is well-documented and linked to nitrification and denitrification processes triggered by increases in soil inorganic nitrogen (NH_4^+ or NO_3^-) (McDonald et al., 2022; Xu et al., 2023). Liebig et al. (2020) observed that N_2O fluxes were highest during the corn and spring wheat phases of rotation in MCLS (mean = 45 μg N_2O-N m^{-2} h^{-1}) and lowest during the soybean and cover crop phases (mean = 20 μg N_2O-N m^{-2} h^{-1}). This suggests that MCLS incorporating perennial grasses or grass-dominated cover crops are more effective at mitigating greenhouse gas emissions (Christenson et al., 2021; Liebig et al., 2020).

Interestingly, substituting N fertilizer with phosphorus (P) or potassium (K) at half the recommended rate reduced cumulative N_2O emissions by 59% in an MCLS (de Carvalho et al., 2022). Additionally, (Abagandura et al., 2019) found no significant effect of grazing on cumulative N_2O emissions.

2.4.2 Methane (CH_4) emission from soils under MCLS

Methane (CH_4) is the second most significant greenhouse gas (GHG) after carbon dioxide (CO_2) in terms of global warming potential (Forster et al., 2007). Even small fluctuations in atmospheric CH_4 levels can have a substantial impact on global warming (Bridgham et al., 2013). CH_4 emissions are influenced by the balance between methanogens and methanotrophs (Zhang et al., 2018). Methanotrophs oxidize CH_4 in aerobic environments, making the soil a CH_4 sink, whereas methanogens release CH_4 under anaerobic conditions (Lee et al., 2018). In mixed crop-livestock systems (MCLS), animal manure is recognized as a notable CH_4 source (USEPA, 2021), with over 70% of CH_4 emissions attributed to enteric fermentation and only 4 - 6% to manure (Conrad, 1996; Maze et al., 2024). As a result, upland soils are typically minor emitters or major sinks of CH_4 (Jin et al., 2019; Liebig et al., 2010).

Christenson et al. (2021) observed no consistent grazing season effects on CH_4 fluxes from perennial grass or continuous corn phases of MCLS. Across study years, soil CH_4 fluxes fluctuated around zero regardless of management practices. Similarly, grazing and nitrogen (N) fertilizer application had no significant impact on soil CH_4 fluxes, which were often characterized by CH_4 uptake (Bratti et al., 2022). Given that CH_4 production is more prevalent under anoxic conditions (Conrad, 1996), low CH_4 emissions in these studies may have been due to the poorly drained soils at the study sites. In such soils, CH_4 diffusion into the soil is the primary factor limiting emissions

(Abagandura et al., 2019). Singh et al. (2020) found no significant effect of cover crops or grazing on daily and cumulative CH_4 fluxes, likely due to the short grazing durations that limited manure and urine accumulation. Similarly, Tang et al. (2013) reported no significant differences in CH_4 uptake between lightly grazed and ungrazed sites.

Contrastingly, some studies reported net CH_4 effluxes in pasture areas compared to cropland soils, potentially due to increased bulk density and reduced aeration porosity caused by animal trampling (Neto et al., 2011). On a subtropical Ferralsol in MCLS subjected to sheep grazing and N fertilization, Piva et al. (2019) observed a net CH_4 influx, suggesting methanotrophic activity. However, CH_4 emission peaks coincided with high soil ammonium levels, possibly due to competition between ammonium and CH_4 for methane monooxygenase, an enzyme critical for CH_4 oxidation (Bédard & Knowles, 1989; Hütsch, 1998). This competition likely reduced CH_4 consumption, resulting in CH_4 release. Similar findings were reported by Zanatta et al. (2010), who observed CH_4 emission peaks shortly (4 – 6 days) after N fertilizer application. These findings highlight the complexity of CH_4 emissions in MCLS and underscore the need to understand the mechanistic drivers of CH_4 fluxes under varying management and environmental conditions.

2.4.3 Carbon dioxide (CO_2) emission from soils under MCLS

Quantifying the impact of management practices on carbon dioxide (CO_2) emissions is essential for optimizing carbon reduction strategies in crop-livestock systems (Liu et al., 2024). According to Barsotti et al. (2013), variations in soil and environmental conditions, management practices, and measurement methods across locations can significantly influence CO_2 fluxes (Sainju et al., 2008).

Increased carbon (C) substrate availability, primarily from sheep feces and urine returned to the soil during grazing, likely stimulates microbial activity, especially under conditions of elevated soil temperature and moisture. This phenomenon was observed in MCLS settings, where grazing treatments showed higher CO_2 fluxes compared to chemical treatment plots (Barsotti et al., 2013). The deposition of excrement, including manure and urine, enhances the decomposition of organic carbon by heterotrophic microbes, contributing to elevated CO_2 emissions. Within MCLS, crop type and the associated root and shoot respiration are critical factors influencing CO_2 fluxes. Perennial crops such as alfalfa exhibit higher CO_2 fluxes due to greater belowground biomass and root respiration compared to annual crops (Barsotti et al., 2013). Alfalfa's larger root biomass relative to durum wheat (*Triticum durum*) and forage grasses (Sainju et al., 2011), has been linked to increased CO_2 fluxes, particularly in systems incorporating a mix of alfalfa (*Medicago sativa*) and grasses compared to annual crops (Sainju et al., 2008). Additionally, forage rotation systems in MCLS are likely to contribute to higher CO_2 emissions than mono-crop systems due to increased biomass production both above and below ground, which intensifies root respiration. Higher cumulative CO_2 fluxes in grazing legume systems compared to grazing grass systems have been attributed to the faster decomposition of legume residues due to their lower C:N ratio (N. Singh et al., 2020a). Furthermore, the decomposition of residual aboveground and belowground biomass from previous crops in ungrazed plots can also emit significant amounts of CO_2 (Singh et al., 2020a).

These findings highlight the complex interactions between management practices, crop type, and environmental factors in determining CO_2 emissions in MCLS, underscoring the importance of tailoring practices to mitigate emissions while maintaining system productivity.

2.5 Effect of MCLS on crop yields

Mixed crop-livestock systems (MCLS) have historically been used for sustaining agricultural production globally, particularly before the widespread use of synthetic fertilizers in the 20th century (Franzluebbers, 2007). Although the extensive application of fertilizers during this period significantly increased crop yields, it also negatively impacted environmental quality. These adverse effects included increased nitrogen leaching into groundwater, eutrophication, and elevated GHG emissions (Huo et al., 2022). Furthermore, the intensive use of commercial fertilizers, especially nitrogen-based ones, contributed to increased soil acidity and the development of degraded soils with diminished responsiveness to further fertilizer applications for maintaining crop yields (Herrero et al., 2010; Sainju et al., 2011). In such cases, MCLS has been identified as a viable strategy to enhance soil quality while sustaining agricultural productivity (de Camargo et al., 2024; Rahman, Larbi, et al., 2019).

Rahman et al. (2019) reported notable improvements in maize grain and biomass yields when optimal combinations of livestock stocking density, maize plant density, and fertilizer rates were applied to Ferric Lixisols. Similarly, Akakpo (2020) demonstrated that farmers practicing MCLS could achieve enhanced grain and fodder yields of legumes through rhizobium inoculation and phosphorus (P) fertilization. In an integrated crop-livestock system evaluated over two growing seasons (2015/2016 and 2016/2017) with soybean and sorghum, de Carvalho et al. (2022) observed higher yields for both crops (except soybean in the first season) when recommended fertilizer rates were used, compared to systems using half the recommended rates. Additionally, better soil conditions in MCLS provided resilience to environmental stresses such as drought and frost, resulting in less yield reduction for soybeans and pastures (Salton et al., 2014). Agostini et al. (2012) attributed increased corn yields in stubble-grazing MCLS to a combination of high stocking rates and shallow tillage practices. Furthermore, Baumhardt et al. (2009) found that limited grazing of dryland wheat forage and sorghum stover improved overall productivity in a wheat-sorghum rotation without significant reductions in grain yields. Similarly, Cicek et al. (2014) reported no adverse yield effects on two subsequent grain crops after grazing green manure, compared to the traditional incorporation of green manure through tillage.

Contrasting findings have been reported in some cases. For instance, Komarek et al. (2021) found no significant agronomic benefits in maize leaf stripping within crop-livestock systems. Similarly, Lazcano et al. (2020) observed no significant yield differences in vineyards subjected to sheep grazing. While neutral effects of MCLS on crop yields are common, literature often highlights other benefits such as improved whole-system economic productivity, enhanced soil health, and water conservation (de Oliveira et al., 2014; Sanderson et al., 2013). The complexity of designing and implementing effective MCLS often contributes to inconsistent outcomes. Negative results are frequently attributed to suboptimal management practices, including insufficient synthetic fertilizer application, inappropriate stocking rates, and inadequate manure management (de Moraes et al., 2014; Peterson et al., 2020). Hence, in a meta-analysis of 66 MCLS studies, Peterson et al. (2020) reported that, when grazing is incorporated into cropping system designs, average crop yields matched those of ungrazed systems across diverse environmental and management contexts. These findings underscore the importance of tailoring MCLS management strategies to specific environmental and system requirements while adhering to best management practices to optimize productivity and sustainability.

2.6 Effect of MCLS on livestock productivity

In mixed crop-livestock systems (MCLS), livestock plays a multifaceted role, contributing to system productivity through the provision of food, feed, draught power, and manure (Herrero et al., 2010; Peden et al., 2007). These systems reduce reliance on commercial feed by utilizing crop or fodder biomass. Moreover, the synergies of MCLS may have benefits that extend beyond enhanced crop yields and livestock weight gain (Addah et al., 2022).

For instance, in a three-year wheat-sorghum-fallow (WSF) rotation system, cattle grazing (*Bos taurus*) resulted in average daily weight gains of 3.8 kg ha^{-1} day^{-1}, with gains ranging from 2.3 to 6.5 kg ha^{-1} day^{-1} (Baumhardt et al., 2009). The study highlighted that this forage rotation sequence consistently produced sufficient stover and forage to support cattle grazing for about one month annually in seven out of eight years. In comparison to MCLS, mixed crop-livestock-tree systems reduced the average daily gain (ADG) of beef heifers by 32% due to the competitive effects of trees on forage growth (da Silveira Pontes et al., 2018). Supporting this observation, Lin et al. (1998) noted that certain forage species, particularly C_3 perennial grasses, can maintain productivity under 50% sunlight at rates similar to those in full-sun conditions. Improved livestock performance has also been reported in other systems. Djallonké rams in an integrated groundnut-sheep system demonstrated higher dry matter and crude protein intake, resulting in superior weight gain (Rahman, et al., 2019b). Similarly, feeding sheep with stripped maize leaves enhanced dry matter intake, daily weight gain, and overall efficiency compared to grazing on native pasture (Addah et al., 2022). This highlights the dual-purpose value of crops, as smallholder farmers often view both forage and seed/grain yields as equally important (Olorunju et al., 1995). Furthermore, the rumen degradation characteristics of crop residues in MCLS are critical determinants of forage quality and, consequently, animal performance (Larbi et al., 1999).

Despite the evident benefits of MCLS, much of the existing research focuses predominantly on crop performance, often overlooking the livestock component. To fully understand the potential of these systems, future studies must examine how MCLS can simultaneously enhance both crop yields and livestock productivity.

2.7 Impact of climate change on MCLS

Climate change is expected to impact the crop, livestock, and grazing components of mixed farming systems in diverse ways, disrupting their interactions and resource flow (Figure 1) (Descheemaeker et al., 2016). These disruptions will, in turn, affect the functioning and performance of the entire system. Projections indicate that mixed farming systems in Africa may experience two major transitions by the 2050s (Thornton & Herrero, 2015). The first involves a decline in the number of reliable crop-growing days, while the second is linked to increases in maximum temperatures during cropping seasons, rising above 30°C. At such temperatures, many staple crops and livestock species are likely to suffer adverse effects.

The IPCC predicts that by 2050, the crop-growing periods in West Africa could shorten by 20%, leading to a 40% reduction in cereal yields and a decrease in cereal biomass for livestock (Zougmoré et al., 2016). Crop suitability is also impacted by changes in the growing season length and the increased frequency of extreme weather events, which raise the likelihood of crop failure (Porter & Semenov, 2005). Higher temperatures are expected to accelerate plant growth cycles, reducing yield potential (Schlenker & Lobell, 2010; Sultan et al., 2013). However, certain crops may benefit from these changes; for example, maize in highland regions could thrive due to warmer temperatures (Thornton & Herrero, 2015), and cassava, a heat- and drought-resistant starch crop, might benefit from increased CO_2 levels (Liu et al., 2008). Additionally, shorter growing periods may help crops avoid drought during grain filling (Asseng et al., 2011).

Climate change will also impact livestock at both the species and breed levels (Zougmoré et al., 2016). Farmers may need to shift to heat-tolerant breeds or species better suited to hotter and drier conditions, such as small ruminants like sheep and goats, which are more resilient to heat and require less water (Lemaire et al., 2014). Specific effects on livestock may include changes in forage availability and quality, water access, mobility, and increased mortality (Powell et al., 2004). Beyond these component-level effects, system-wide changes in mixed farming systems due to climate change are also anticipated (Descheemaeker et al., 2016).

For example, Masikati et al. (2017) found that climate change impact on maize grain yields varied by herd size: a reduction of 9%, 3%, and -2% was observed for farmers with no cattle, small herds, and large herds, respectively. For maize stover, the declines were 5%, 6%, and 4%, respectively. Conversely, sorghum and groundnut yields, both grain and stover, were unaffected (Masikati et al., 2017). Similarly, Thornton & Herrero, (2015) noted that the effects of climate change on crop-livestock systems differ across farm types and crops. Under a high-emission scenario (RCP8.5), Rigolot et al. (2017) projected that climate change could significantly limit production in crop-livestock systems regardless of farm size. However, these systems might shift toward a greater reliance on livestock since animals are better adapted to arid and variable climates than crops. Livestock can feed on crop residues when grain harvests fail and utilize spatial and temporal variations in feed availability (Morton, 2007; S. Vetter, 2005). As annual crops become less viable, there may be a shift toward livestock-oriented systems (Jones & Thornton, 2009). Climate-induced biome shifts, such as those affecting grasslands and rangelands, will likely influence grazing potential in Africa. However, the interactions between climate change and other factors like fire and grazing introduce uncertainties, making precise predictions challenging (Descheemaeker et al., 2016).

Despite the importance of mixed systems like MCLS in adapting to climate change, they have been underrepresented in global agricultural assessments (Herrero et al., 2010; Thornton et al., 2014). For instance, IPCC reports often separate discussions of crops, livestock, fisheries, and forestry, without integrated assessments of mixed systems (Thornton et al., 2014). Moreover, research on the whole-farm impacts of climate change, including future projections for mixed systems, remains limited (Ghahramani & Moore, 2016; Masikati et al., 2015). However, Thornton et al. (2014) noted that assessments can only analyze what has been published, underscoring the need for more comprehensive studies on these systems.

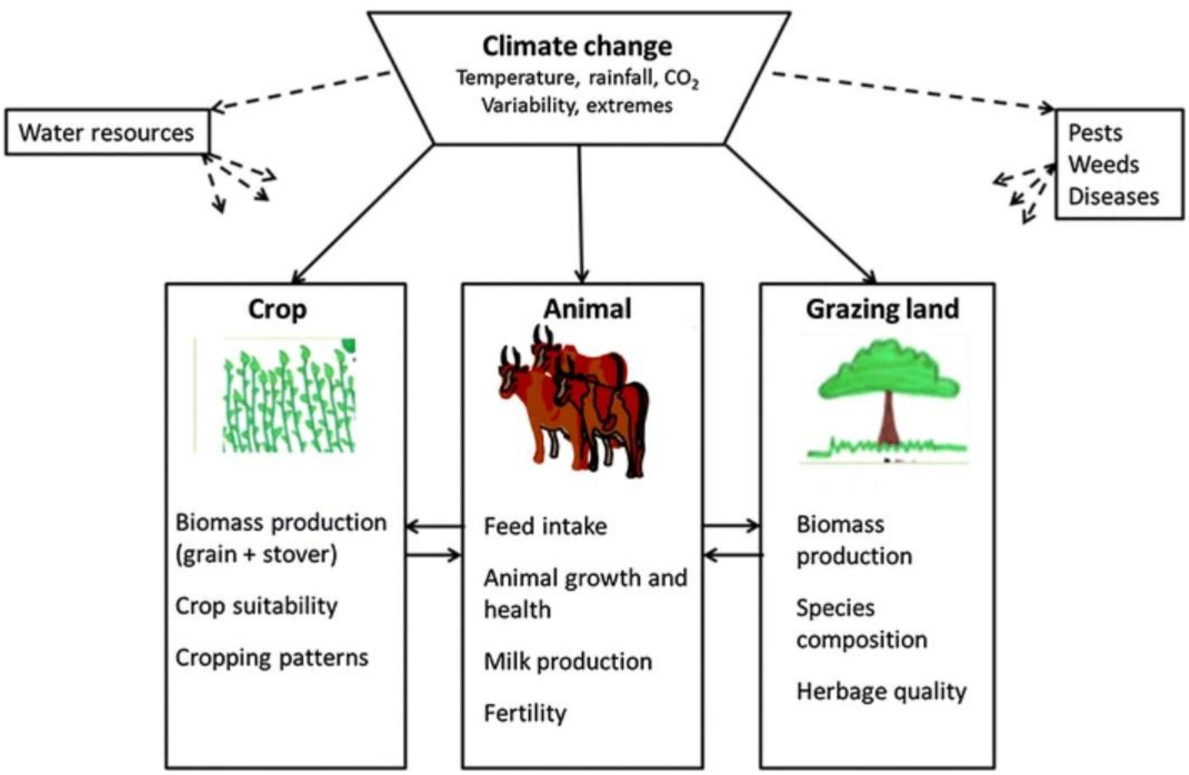

Figure 1. Adapted from Descheemaeker et al. (2016): Schematic representation of the effects of climate change on mixed crop–livestock systems.

2.8 Contribution of simulation models to MCLS

Mixed crop-livestock systems (MCLS) face significant challenges in meeting the growing food demands of a rising global population and adapting to shifts in dietary preferences, particularly in urban areas with increasing incomes (Herrero et al., 2010; Tarawali et al., 2011). These pressures are compounded by climate change, which places additional strain on these systems, requiring them to adapt and innovate. MCLS are inherently complex, involving interrelated biophysical components such as crops, livestock, soil, climate, and vegetation, alongside socioeconomic factors like markets, off-farm income, and management decisions (Masikati et al., 2017). To improve the efficiency and sustainability of these systems, research must identify potential intervention points by analyzing the interaction of these components across spatial and temporal scales (Masikati et al., 2017).

Simulation modeling has proven to be a valuable tool for analyzing the intricate interactions within MCLS and assessing overall system efficiency (de Wit, 1992). For example, Zingore et al. (2009) combined multiple models to evaluate strategies for enhancing the productivity and profitability of resource-constrained crop-livestock farms. Data collection was facilitated using the Integrated Modelling Platform for Mixed Animal Crop Systems (IMPACT), which was linked to the Household Resource Use Optimization Model (HROM). HROM was used to optimize net cash income, while APSIM (Agricultural Production Systems sIMulator) and RUMINANT models simulated nutrient resource management in crop and milk production, respectively. Additionally, the Dynamic North Florida Dairy Farm Model (DyNoFlo), which incorporates Markov chain simulations of cow flows and crop model simulations for historical climate years (e.g., El Niño and La Niña years), was utilized to evaluate nitrogen leaching on dairy farms (Cabrera et al., 2006). In another study, Kragt et al. (2012) assessed the cost-effectiveness of soil carbon sequestration by integrating biophysical modeling using APSIM with whole-farm economic modeling via the Model of an Integrated Dryland Agricultural System (MIDAS). However, results from field studies often show mixed outcomes due to the short duration of crop-livestock interactions. To address this, Rai et al. (2022) developed a simplified simulation methodology using the Decision Support System for Agrotechnology Transfer (DSSAT) to evaluate the long-term effects of cover crop grazing on maize production.

Similarly, Moreau et al. (2013) introduced CASIMOD'N, an integrative model designed to assess the impact of farming systems on nitrogen dynamics at the catchment level. This model includes components such as Topmodel-based Nitrogen Transfer and Transformation (TNT2), which accounts for spatial processes like nitrate leaching and its effects on downstream areas (Oehler et al., 2009), TOURNESOL, which ensures consistency between crop allocation and manure production, and FUMIGENE, which allocates organic and mineral fertilizers (Chardon et al., 2012). Another study by Dueri et al. (2007) employed a dynamic model (Stella CH-farm) to analyze nitrogen losses and exports in dairy and arable farming systems. Rufino et al. (2011) utilized NUANCES-FARMSIM to simulate interactions at the village level, revealing that long-term grazing and crop residue removal can lead to declines in soil carbon stocks. Prolonged dry seasons and reduced residue availability may also result in cattle losses, impacting draught power and manure production. However, these effects can be mitigated by utilizing residues from non-livestock farms, which can sustain up to 30% of cattle feed during the dry season. Parsons et al. (2011) developed an integrated crop-livestock model to evaluate the biophysical and economic outcomes of farming practices in sheep systems. The model, built using Vensim™, integrates scientific and practical knowledge about sheep management, flock dynamics, nutrient partitioning, labour, and economics. It combines sheep production and manure data from the Small Ruminant Nutrition System (SRNS) with weather, crop, and soil dynamics simulated daily by APSIM. The evaluation confirmed the model's effectiveness in capturing the complex interactions between crops, livestock, and farmers.

Simulation models thus serve as critical tools for assessing the sustainability and productivity of MCLS. However, their application in Sub-Saharan Africa (SSA) remains limited, despite their potential to address pressing challenges in complex farming systems (Masikati et al., 2017). Key barriers include insufficient data (biophysical and socioeconomic), a lack of skilled expertise, and the absence of validated modeling frameworks. To address these gaps, there is a pressing need to develop an integrated framework that incorporates detailed data from typical crop-livestock farms at varying scales to evaluate and enhance the productivity and resilience of MCLS in SSA.

2.9 The SIMPLACE framework

2.9.1 Overview

The Scientific Impact Assessment and Modelling Platform for Advanced Crop and Ecosystem Management (SIMPLACE) is an open-source software platform developed at the University of Bonn. Its design is rooted in the principle of creating tailored model structures to address specific research or analytical questions (Enders et al., 2023). The latest version, SIMPLACE v5.0, emphasizes three key paradigms: flexibility, performance, and transparency. While typical simulation experiments can be efficiently conducted on personal computers, SIMPLACE includes advanced features to address performance challenges, supporting computationally demanding tasks such as gridded simulations, model calibration, scenario analysis, and uncertainty analysis (Enders et al., 2023). The platform is designed for compatibility with multiple systems, including High-Performance Computing (HPC) environments, enabling scalability as HPC systems become increasingly accessible in research institutions (Vetter, 2013). Implemented using the Java® programming language, SIMPLACE leverages an object-oriented design (Gamma et al., 1995) and incorporates specialized packages for advanced input/output handling, relational database management, internal data exchange, and multi-threaded simulations (Enders et al., 2023). SIMPLACE v5.0 supports various external data input formats, including SQL databases, CSV, JSON, NetCDF, DBF, and XML. It can also directly read JSON and XML data streams from URL-based servers (Enders et al., 2023).

2.9.2 ModelSolution

The ModelSolution in SIMPLACE is where all linkages and rules for data exchange and processing between I/O interfaces, resources, and SimComponents are explicitly defined (Enders et al., 2023). This structure provides maximum flexibility for designing and testing complete model frameworks. Multiple SimComponents can be assembled in a predefined execution sequence to address specific research problems or test scientific hypotheses. As described by Enders et al. (2010, 2023) the developers of the SIMPLACE framework, a ModelSolution is specified using an XML file format with five key sections: (i) constant variables (<variables>), (ii) interfaces (<interfaces>), (iii) resources and data transformers (<resources>), (iv) SimComponents structure and linkages (<simmodel>), and (v) outputs (<outputs>). Additionally, a model description section (<description>) is included for documentation and quality checks.

SimComponents are modular software units that comprise mathematical formulations for one or more processes and can be regarded as sub-models. These SimComponents are declared as <simcomponent> objects within the <simmodel> section, where they are executed in sequence and linked to other SimComponents or <resource> objects. SIMPLACE offers a wide array of SimComponents for modeling key processes in crop growth and agroecosystems, such as crop phenology, shoot growth, biomass accumulation, yield formation, water and nitrogen demands, root growth, soil temperature and water dynamics, root water uptake, and soil carbon and nitrogen dynamics (Enders et al., 2023). Many SimComponents are derived from well-established models, which are also available in SIMPLACE as integrated components. These include generic crop models ranging from simple to highly detailed, such as LINTUL 2 and 5 (Van Oijen & Lefelaar, 2008; Wolf, 2012), GECROS (Yin & van Laar, 2005), and SUCROS (Goudriaan & van Laar, 2012). Users can combine SimComponents to create model configurations tailored to the target system, ensuring compatibility with available input data and enabling the quantification of uncertainties related to model structure and detail.

The flexibility and advanced interfacing capabilities of SIMPLACE also facilitate the integration of external models without requiring modifications to the sub-module source code (Enders et al., 2023). This feature makes it suitable for developing integrated assessment models that quantify the effects of various drivers on complex systems. However, despite the critical importance of mixed crop-livestock systems (MCLS) to global food security, integrated assessments of these systems remain limited, with the work of Srivastava et al. (2025) being a notable exception. This thesis builds on this gap by using actual farm-scale data to calibrate and validate existing crop-livestock models within SIMPLACE. The aim was to evaluate the potential of these models to simulate outputs from typical crop-livestock farms based on real-world data, thereby enhancing the understanding and predictive capacity of these systems.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Environmental and management factors affecting greenhouse gas fluxes from soils in mixed crop-livestock systems– A meta-analysis

Here, a meta-analysis of 21 independent mixed crop-livestock system (MCLS) studies was conducted to compare soil greenhouse gas (GHG) fluxes from croplands of MCLS with fluxes from croplands within purely arable systems. This sub-chapter therefore focuses on Objective 1 of the thesis, to determine the response patterns of nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) emissions in MCLS across diverse regions and management scenarios.

3.1.1 Data collection

3.1.1.1 Literature search strategy

A comprehensive literature search was conducted using Scopus (https://www.scopus.com/), ScienceDirect(https://www.sciencedirect.com/), and Google Scholar (https://scholar.google.com/) to identify peer-reviewed articles published between 1 January 2003 and 31 December 2022, that examined the GHG response of MCLS. The last search was done in May 2023 with the keywords: ("crop-livestock*") AND ("soil greenhouse gas") OR ("methane") OR ("CH_4") AND ("carbon dioxide") OR ("CO_2") AND ("nitrous oxide") OR ("N_2O") AND ("soil emission"). In total 1,222 studies were identified from the database searches. The reference list within the selected research articles was also gleaned to identify studies that meet our initial selection criteria (see section 3.1.1.2). The literature search adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (Appendix 1) (Moher et al., 2009).

3.1.1.2 Study selection criteria

The following criteria were used to select suitable studies: (1) studies focusing on spatially integrated crop-livestock systems (field-level integrated systems) with an arable (control) system, i.e., croplands not grazed or subjected to manure application. Studies on crop-livestock-forest systems or livestock-grassland systems were excluded; (2) field experiments were required, excluding life cycle assessment studies; (3) studies had to report or allow calculation of mean cumulative/annual soil GHG (N_2O, CH_4, CO_2) emissions for both integrated treatment and control; (4) replication number (n), standard deviation (SD), or standard error (SE) had to be provided; (5) only original research, datasets, or dissertations were included, excluding reviews, book chapters, or conference proceedings. In total, 99 observations from 21 papers (2013–2022) across two continents (Figure 1) met these criteria and were included in this meta-analysis (Table 1). Among them, 20 papers reported soil N_2O emissions, 14 reported CH_4 emissions, and 7 reported CO_2 emissions (Table 1).

3.1.1.3 Data extraction

For each study, data were extracted on cumulative/annual GHG emissions from MCLS treatments and their controls (arable treatments). GHG measurements from all studies were standardized, converting observed values to (kg CO_2-C ha^{-1}, kg CH_4-C ha^{-1}, kg N_2O-N ha^{-1}) for analysis. Besides the response variable, our database included experimental design details, experiment period, and standard deviation when available. Information from the materials and methods sections, results, tables, and figures was meticulously extracted. When data appeared only in figures, values were obtained using the figure calibration plugin in Fiji (ImageJ) software (v.1.5.4f). Similarly, when standard deviations (SD) were not reported, they were computed from the reported replication number (n) and standard error (SE) values using the equation:

$$SD = SE\ x\ \sqrt{n} \tag{1}$$

The dataset was categorized based on various moderating factors, including climate, soil and drainage classes, crop species, livestock type, stocking density, tillage practices, fertilizer type, and nitrogen (N) application rates. Climate data were classified using the updated Köppen-Geiger climate classification map (Kottek et al., 2006). Soil texture, drainage, and soil classes were derived from the Harmonized World Soil Database v2.0 (Nachtergaele et al., 2023). These categorizations utilized latitude and longitude coordinates associated with each study. Crop species were grouped into functional categories based on FAO definitions (FAO, 2020), while livestock species were divided into small ruminants (sheep) and cattle. Stocking densities were categorized as low, moderate, or high, based on descriptions in the original studies. Tillage practices were grouped into conservation tillage (CST), including no-till, strip-till, and ridge-till, and conventional tillage (CNT), which included mouldboard and chisel ploughing. Fertilizer application was treated as binary (yes/no), with 'yes' indicating fertilizer use and 'no' indicating no application. Fertilizers were further classified into nitrogen (N) fertilizers (e.g., N-P-K, urea, UAN), phosphorus (P) fertilizers (e.g., TSP, SSPf), and organic fertilizers (e.g., compost). Nitrogen application rates were divided into low (≤120 kg N ha^{-1}) and high (>120 kg N ha^{-1}) levels, following (Shakoor et al., 2021). If information about tillage or fertilizer application was unavailable, it was assumed that neither tillage nor fertilizer application occurred for those observations.

3.1.2 Data analysis

Analyses were performed using the randomForest package (Liaw & Wiener, 2002) and the boot package (Cathy & Ripley, 2017; Davison & Hinkley, 1997) in R version 4.3.1. Funnel plots were utilized to visually inspect for potential publication bias, and the "trim and fill" method (Duval & Tweedie, 2000) was applied to test the robustness of results against funnel plot asymmetries. An Egger test indicated no significant evidence of publication bias ($z = -1.09$, $p = 0.27$). Rosenberg's fail-safe number (Rosenberg, 2005) suggested that 9,618 additional studies would be needed to nullify the statistical significance of the combined effect size in this analysis.

To evaluate the impact of the MCLS and related variables (climate, stocking density, fertilizer, drainage class, soil texture, crop type, livestock type, tillage, and MCLS type) on soil GHG emissions, we computed the natural log of the response ratio (lnRR) following the approach outlined by Borenstein et al. (2009);

$$\mathrm{In}RR = \mathrm{In}\left(\frac{\bar{X}_{integrated}}{\bar{X}_{arable}}\right) \tag{2}$$

Where $\bar{X}_{integrated}$ and $\bar{X}_{arable}$ are the mean values of N_2O, CH_4, and CO_2 emission from MCLS (integrated) and arable (control) systems, respectively. If the RR value is zero, RR > 1, and RR < 1, it means the absence, positive, or negative impact, respectively, of the integrated MCLS on soil GHG emissions compared to the arable system (control). The variance (v) of In*RR* was calculated as follows:

$$V = \frac{SD_{integrated}^2}{N_{integrated} M_{integrated}^2} + \frac{SD_{arable}^2}{N_{arable} M_{arable}^2} \tag{3}$$

Where $N_{integrated}$, $SD_{integrated}$, $M_{integrated}$ versus N_{arable}, SD_{arable}, M_{arable} are the number of replicates, standard deviation, and mean of the response variables in integrated (grazing) and control (ungrazed) plots respectively. Weight was then allocated to each In*RR* observation in proportion to the inverse of within-study variance (1/v).

The bias-corrected and accelerated (Bca) bootstrapping method from the R boot package was used to calculate the overall mean effect size and its 95% confidence interval (CI), utilizing 4,999 iterations (Pittelkow et al., 2015). A significant effect of the integrated MCLS is indicated if the 95% CI does not include zero. For easier interpretation, the ln*RR* was back-transformed to calculate the percentage change (Δln*RR*) using the formula

$$\Delta InRR = [\exp(InRR) - 1] \times 100 \quad (4)$$

To identify key variables influencing the prediction of GHG emissions from the integrated MCLS, a non-parametric random forest analysis was performed (Pittelkow et al., 2015) using the randomForest package in the R programming environment. Variable importance was ranked using ln*RR* as the response variable and categorical predictors, including crop type, livestock type, tillage, drainage class, stocking density, soil texture, climate, fertilizer type, nitrogen (N) fertilizer application rate, and MCLS type. The random forest (RF) permutation importance metric, which is more reliable for predictors with diverse or numerous categories (Strobl et al., 2007), was employed. Following Peterson et al. (2020), variable importance was assessed through a series of steps: (1) The percentage increase in mean squared error (MSE) was calculated by removing each variable from the model, with an increase in MSE indicating reduced model accuracy. (2) The most important variable (the one causing the highest percent increase in MSE) was normalized to a value of 1. (3) The relative importance of the remaining variables was calculated in relation to this benchmark.

3.2 Impact of fertilizer applications on grain and vegetable yields in smallholder Mixed Crop-Livestock systems (MCLS) in Burkina Faso and Ghana..

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Mixed crop-livestock (MCL) systems have the potential to boost crop yields, enhance nutrient cycling, and reduce reliance on chemical fertilizers. However, most studies supporting these claims were not conducted under real-world conditions of small-scale farmers or followed an integrated approach. Hence, this sub-chapter focuses on Objective 2 of the thesis, which employed a survey activity that seeks to understand and quantify the potential impact of current fertilizer application practices on grain and vegetable yields in smallholder MCLS of Ghana and Burkina Faso.

3.2.1 Description of study location

Farm surveys were conducted in the Loumbila (12° 50' N, 1° 39' W), Ziniaré (12° 57' N, 1° 29' W), and Zitenga (12° 73' N, 1° 31' W) communes of the Oubritenga province of Burkina Faso, as well as in the Kassena Nankana (10° 91' N, 1° 13' W), Builsa North (10° 80' N, 1° 16' W) and Bongo (10° 88' N, 0° 85' W) districts of the Upper East Region of Ghana (Figure 2). These surveys covered the 2021/2022 (Ghana) and 2022/2023 (Burkina Faso) cropping seasons (i.e., the annual cycle of crop production activities).

3.2.2 Climate

The study locations fall within the Sudan Savannah zone of West Africa. Daily mean temperature (°C) and rainfall (mm) data for this zone were sourced from the AgERA5 dataset, the fifth generation of Agrometeorological European Reanalysis, available through the Copernicus Climate Data Store (Boogaard et al., 2020). Temperature (°C) and rainfall (mm) data are presented as the mean values for all study areas within each country. In Ghana, the total rainfall recorded was 625.80 mm in 2021 and 830.66 mm in 2022 (Figure 3c-d), with mean temperatures of 27.6 °C and 27.0 °C, respectively. In Burkina Faso, total rainfall amounted to 608.20 mm in 2022 and 529.47 mm in 2023 (Figure 3a-b), while the mean temperatures were 27.8 °C in 2022 and 28.5 °C in 2023 (Figure 3a-b).

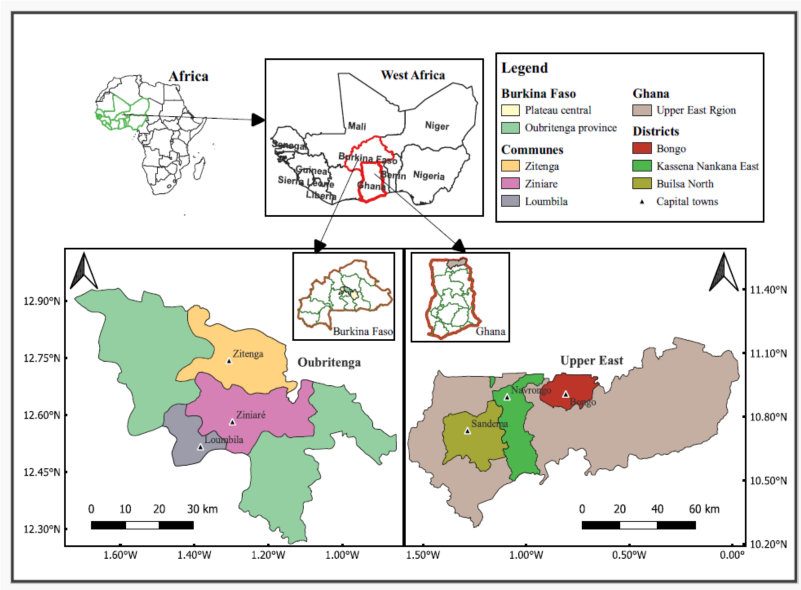

Figure 2. A map showing the communes and districts where the surveys were conducted in Burkina Faso and Ghana, respectively.

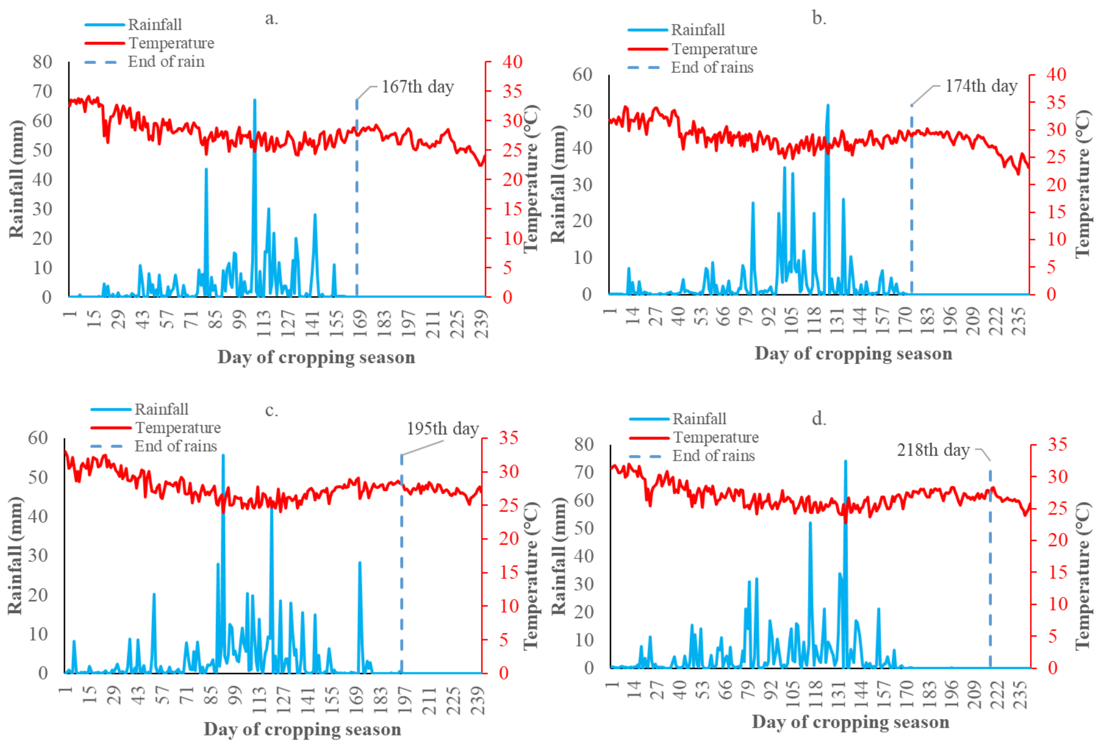

Figure 3. Daily rainfall and temperature of surveyed communes in Burkina Faso (a) 2022, (b) 2023 and districts in Ghana (c) 2021 and (d) 2022. The dotted vertical line marks the final day of rainfall in the cropping season.

3.2.3 Soil

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).

3.2.4 Survey procedure

In Burkina Faso and Ghana, ten and five enumerators, respectively, were trained to conduct surveys. Data were collected through face-to-face interviews using a digital questionnaire hosted on the KoboToolBox platform and deployed via KoBoCollect (v2023.1.2 in Burkina Faso and v2022.2.3 in Ghana). A total of 101 MCLS farmers participated in the study (58 in Burkina Faso and 43 in Ghana), covering 361 fields (143 in Burkina Faso and 218 in Ghana). Agronomic management data for each farmer's field were obtained through questionnaires and field measurements. For instance, crop yield data for the first cropping season were gathered from farmers' responses, while yields for the second season were measured from a 5 × 5 m subplot within each main plot. This process required two field visits: the first to set up the 5 × 5 m quadrat using field pegs (Appendix 6) and to record field information (e.g., GPS coordinates and area in square meters), and the second for harvesting and weighing the yield from the subplot. In cases where crops had reached physiological maturity at the time of data collection (e.g., early-planted millet), a single visit was sufficient to gather all necessary data.

After the survey, a review of individual crop fields for data completeness led to the exclusion of 44 fields. These fields were removed because they were inaccessible, preventing the collection of essential data such as coordinates, area (sqm), and yield. Additionally, seven fields were excluded due to insufficient sample sizes (n = 1) for certain crops, including rice, sesame, zucchini, cucumber, and carrot in Burkina Faso, as well as Bambara groundnut and eggplant in Ghana. A root and tuber crop, sweet potato (n = 3), was also excluded in Ghana. As a result, the study dataset consisted of 307 individual grain and vegetable crop fields, comprising 123 fields from Burkina Faso and 184 from Ghana. Summary statistics for the final sample are provided in Table 1.

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

3.2.5 Data collection

Each of the 307 crop fields was mapped using a Global Positioning System (GPS) to determine the cultivated area for each crop. Agronomic management and yield data collected included planting dates, fertilizer application schedules, harvest dates, types of chemical fertilizers used, quantities of fertilizer applied (kg plot^{-1}), fertilizer application methods (broadcast, side placement, or furrow), and grain or fruit weight (kg per 25 m^2). To assess the impact of agronomic management practices on yield, the analysis focused on fertilizer source, application method, timing of chemical and manure fertilizer application, and nitrogen application rates (kg ha^{-1}).

3.2.5.1 Fertilizer management

MCLS farms were classified into four fertilizer source categories based on the type of fertilizer used: no fertilizer, manure, chemical fertilizer, and combined (manure + chemical fertilizer). Fertilizer placement methods were recorded and categorized as broadcast, side placement, or furrow. The timing of chemical fertilizer and manure application was calculated using Equations 4 and 5, respectively. For manure, an average nitrogen (N) content of 1.6% was assumed, representing contributions from cattle, small ruminants, pigs, and poultry (Sileshi et al., 2017). The N content of chemical fertilizer was determined using Equation 6. The total nitrogen applied to each crop field was calculated as the sum of the N contributions from both manure and chemical fertilizer (Equation 7).

$$\Delta T = Df - Dp \quad (5)$$

$$\Delta T = Dp - Df \quad (6)$$

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 (Appendix 3). On the other hand, manure application was considered optimum when Tr was between 0 to 3 weeks before planting (WABP).

$$N_{CHEM} = \frac{(Q\ X\ C)}{100} \quad (7)$$

$$N_{TOTAL} = N_{CHEM} + N_{MAN} \quad (8)$$

The N rate (kg ha^{-1}) was considered low if $N_{TOTAL} < N_{CR}$ or recommended if $N_{TOTAL} \geq N_{CR}$. Where N_{CHEM} 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, N_{MAN} is the amount of N in manure, N_{TOTAL} is the total amount of N (kg ha^{-1}) applied, and N_{CR} is the crop type and country-specific N rate (kg ha^{-1}) recommendation (Appendix 4).

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.

3.2.5.2 Yield determination

The yields of both grain and vegetable crops during the second cropping season were measured using a 5 x 5 m quadrat in each crop field. Grain crops were harvested at physiological maturity, processed (e.g., dehusking, shelling), and measured. Relatively low rainfall and high temperatures during the physiological maturity phase provided favourable drying conditions for the grains. Likewise, vegetables were harvested at physiological maturity and weighed to determine their fruit yield. All yield measurements were standardized and reported in kilograms per hectare (kg ha^{-1}).

3.2.6 Statistical analysis

Mean grain and fruit yields were analysed to evaluate the effects of fertilizer source, application method, timing, and nitrogen rate (kg ha^{-1}) using one-way Analysis of Variance (ANOVA). Normality of the data distribution was evaluated using visual inspection of Q–Q plots. Levene's test was employed to examine the assumption of homogeneity of variances. When this assumption was violated, Welch's one-way ANOVA was applied as an alternative approach to account for unequal variances (Wilcox, 2003). When significant differences were detected, Tukey's post-hoc test was used for mean comparisons, with statistical significance set at a 5% probability level or less ($P \leq 0.05$).

To assess the accuracy of farmer-reported yields compared to measured yields, regression analysis was conducted, correlating reported yields with measured yields. The coefficient of determination (R^2) from the linear model was used to evaluate the agreement between the two. Reported yields showed a strong alignment with measured yields, with R^2 values as follows: 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) (Appendix 5). All statistical analyses were conducted using R statistical software (version 4.3.1).

3.3 Calibration and validation of SIMPLACE model for simulation of mixed crop-livestock systems in West Africa.

Mixed crop-livestock systems (MCLS) enhance farm productivity and resource use efficiency by utilizing complex interactions among crops, livestock, and grassland. However, determining optimal system performance through observational assessments necessitates numerous field experiments, which are often constrained by limited time and resources. To address these challenges, this sub-chapter focuses on Objective 3 of the thesis by utilizing the SIMPLACE modelling framework to simulate the outputs of typical crop-livestock systems. The model is calibrated and validated using actual farm-scale data collected from mixed crop-livestock systems in Ghana and Burkina Faso.

3.3.1 Integrated model description

3.3.1.1 Crops and grass growth simulation modules

In this study, crop yield and grass biomass were simulated by integrating the SIMPLACE <LINTUL5> and SIMPLACE <Grassland> solutions within the SIMPLACE modelling framework. The LINTUL5 model simulates potential yields under optimal conditions, considering factors such as solar radiation and temperature. Additionally, water-limited yield simulations account for constraints imposed by temperature, radiation, water availability, and soil properties, while nutrient-limited yield simulations incorporate nutrient restrictions. Biomass production is modelled based on intercepted radiation and its allocation to various crop organs according to developmental stages. Phenological development is determined by the accumulation of thermal time, while photosynthesis and crop growth rates are estimated using intercepted light and radiation use efficiency. The crop growth cycle is simulated from emergence to physiological maturity. The parameters of the model and values used for the crop types (maize, millet, sorghum, peanut) are shown in Table 2.

Table 2. Parameters of the SIMPLACE model and values used for the crop types

	Values used in the model				
Parameters	**Maize (var. Obatanpa)**	**Millet (var. CIVT)**	**Sorghum (var. CSM 335)**	**Peanut (var. Fleur 11)**	**Units**
Temperature sum from emergence to anthesis (TSUM1)	880	1230	750	422	°C day
Temperature sum from anthesis to maturity (TSUM2)	900	400	540	1285	°C day
Radiation use efficiency* (RUE)	3.6-1.1	3.4-2.9	3.6-3.5	3.2-1.8	gMJ^{-1}
Specific leaf area (SLATB)	0.018-0.015	0.024-0.017	0.03-0.028	0.016-0.014	m^2g^{-1}
Maximum Relative increase in LAI (RGRLAI)	0.03	0.03	0.03	0.03	$haha^{-1}d^{-1}$
Reduction in yield per degree hour above a threshold temperature	0.0025	0.0025	0.0025	0.0025	
Maximum N concentration in storage organs	0.0152	0.0152	0.01	0.0392	gg^{-1}
Maximum P concentration in storage organs	0.0027	0.0027	0.0027	0.0039	gg^{-1}
Maximum K concentration in storage organs	0.032	0.032	0.032	0.0091	gg^{-1}
Fraction of crop N uptake by biological fixation (NFIXF)	0	0	0	0.8	
Critical N concentration as fraction of maximum N concentration (FRNX)	1.0	1.0	1.0	0.7	gg^{-1}
Critical P concentration as fraction of maximum N concentration (FRPX)	1.0	1.0	1.0	0.7	gg^{-1}
Critical K concentration as fraction of maximum N concentration (FRKX)	1.0	1.0	1.0	0.5	gg^{-1}

3.3.1.2 Livestock population growth simulation module

The daily changes in livestock population across six age-gender classes (JuvenileMale, SubAdultMale, AdultMale, JuvenileFemale, SubAdultFemale, AdultFemale) were simulated using the livestock population dynamics module. This simulation is based on tracking the number of animals within each class and their transition from one age category to the next. Population changes were driven by key parameters: birth rates (defined as "Parturition," or the number of births per adult female per year), class-specific mortality rates (e.g., "Adult Female Mortality Fraction" per year), transition rates (as defined in Equation 4), intake rates, and offtake rates (expressed in a total number of animals). Birth rate calculations rely on the input parameter "Parturition," which may be adjusted using the "Prolification" fraction to account for the survival rate at birth. Surviving offspring are then divided into male and female categories using the user-defined "Female At Birth" fraction. In periods of feed energy deficiency, birth rates are further adjusted using the "Production Nutrition Index," a daily value calculated by the "Livestock Energy Stress" component. The transition of animals from juvenile to sub-adult and from sub-adult to adult classes is governed by the "gamma" factor, which quantifies the rate of progression between age classes.

$$\Gamma = \frac{surv^{d-1} - surv^{d}}{1 - surv^{d}} \tag{9}$$

Where "Γ" is the gamma factor, "surv" is the survival probability (as fraction 1 - mortality fraction – offtake fraction) and "d" is the user-defined timespan of an animal staying in a given age-gender class (in years)

The computation of daily changes in animal numbers for each age-gender class was further refined by incorporating feedback mechanisms between mortality rates and energy supply deficits. These deficits are captured through the "Maintenance Nutrition Index," which is derived from the "Livestock Energy Stress" simulation component. Mortality is subsequently adjusted based on the input parameter "Maintenance Nutrition Mortality Factor," allowing energy-related stress to dynamically influence population changes.

$$MF = (1 - MNI) \times MMF + MNI \tag{10}$$

Where "MF" is the mortality factor, "MNI" is the maintenance nutrition index, "MMF" is the maintenance nutrition mortality factor and "MNI" is the maintenance nutrition index.

3.3.2 Model inputs

3.3.2.1 Weather data

AgERA5 is a high-resolution, global climate dataset developed by the Joint Research Centre (JRC) of the European Commission (https://cds.climate.copernicus.eu/datasets/sis-agrometeorological-indicators?tab=overview). It is specifically tailored for agricultural applications and provides consistent, daily meteorological data derived from the ERA5 reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Covering the period from 1979 to the present, AgERA5 offers climate variables that are essential for agricultural modelling and analysis, such as temperature, precipitation, solar radiation, wind speed, humidity, and more. The data is spatially aggregated to a resolution of 0.1° x 0.1° (~10 km), making it highly suitable for both regional and global scale studies.

AgERA5 incorporates post-processing steps to better match the needs of the agricultural community, including bias correction techniques and adjustments for variables relevant to crop and soil modelling.

3.3.2.2 Soil data

The model required various soil characteristics, including pH, bulk density (kg m^{-3}), organic carbon and nitrogen concentrations (expressed in kg kg^{-1}), soil texture components (percentages of clay, silt, and sand), as well as key hydrological properties such as field capacity and wilting point (measured in mm m^{-3}). These parameters were extracted from the ISRIC-WISE (International Soil Reference and Information Centre – World Inventory of Soil Emission Potentials) database, based on the coordinates of the central point within each MCL farm/parcel.

3.3.2.3 Crop management and yield data

Agronomic management data were collected for individual farmer fields; 143 in Burkina Faso and 218 in Ghana (detailed information of study sites are found in chapter 3.2.1) using a combination of structured questionnaires and direct field assessments. Crop-specific fertilizer rates were gathered from farmer's responses. Similarly, yield information for the initial cropping season (2021 in Ghana; 2022 in Burkina Faso) was primarily based on farmer-reported estimates, whereas data for the subsequent season (2022 in Ghana; 2023 in Burkina Faso) were obtained through standardized plot-level measurements. Specifically, yield was assessed from a designated 5 × 5 m subplot established within each main field. Data collection involved two field visits: the first to construct the subplot using field pegs and to document field metadata, including GPS coordinates and field dimensions (in square meters); and the second to harvest and weigh yield from the subplot. In instances where crops had already reached physiological maturity (e.g., early-sown millet), a single visit was sufficient to complete all necessary measurements.

3.3.2.4 Livestock population data

Utilizing the same study locations outlined in Chapter 3.2.1 and data collection methodologies, data on livestock populations including cattle, sheep, goats, pigs, and poultry were collected. For each MCLS household, the number and average weight of animals were recorded across six distinct age-gender categories: Juvenile Male, Sub-Adult Male, Adult Male, Juvenile Female, Sub-Adult Female, and Adult Female (see Appendix 7-8).

3.3.3 Datasets used for model calibration

For model calibration, empirical data collected from crop-livestock farms through survey activities were utilized. These data included fertilizer application rates and crop yields for maize, millet, sorghum, and peanut selected based on their widespread cultivation by farmers and the availability of relevant datasets for model calibration.

3.3.4 Model evaluation

The model performance was evaluated based on the bias quantity (BQ), mean residual error (MR) and the root mean squared error (RMSE). Evaluating model performance using observed data is essential, and statistical analysis is recognized as the key method for comparing model outputs with observed data (Yang et al., 1999; Yang et al., 2014). Hence, the relationship between the observed and simulated crop yield, and livestock population are assessed using the following methods in Table 3.

Table 3. Measures of agreement between observed data and model-simulated values

Name	Equation	Meaning and range
Bias Quantity	$B_i = O_i - S_i$	Bias measures the average difference between measured and calculated values, a positive value means under-prediction, whereas a negative value means over-prediction (Yang 2020).
Mean Residual Error	$MR = \frac{S_i - O_i}{O_i}$	MR Represents the percentage difference between simulated and observed data. It evaluates the accuracy of the simulated values compared to the statistical (observed) data (Srivastava et al., 2025).
Root Mean Squared Error	$RMSE = \sqrt{\frac{1}{n}\sum(S_i - O_i)^2}$	RMSE comprises both precision and accuracy and has the same units as the variable of interest. Hence it indicates how far off predictions are from the actual observed values. Very sensitive to outliers.
Coefficient of determination	$R^2 = 1 - \frac{\Sigma_{i=1}^{n}(O_i - S_i)^2}{\Sigma_{i=1}^{n}(O_i - \bar{O})^2}$	From 0 to 1.R^2 close to 1 indicates model fits very well, and close to 0 indicates poor performance of model in prediction.

S_i $= simulated\ values, O_i = observed\ values, \bar{O} = mean\ of\ observed\ values, n = number\ of\ observations$

3.4 Applying the validated model for the estimation of climate change effect on MCLS

In Sub-Saharan Africa, smallholder mixed crop-livestock systems (MCLS) are projected to remain integral to achieving food security. Nonetheless, their capacity to sustain rising food demands requires critical evaluation within the context of ongoing and anticipated climate change. Hence, this sub-chapter focuses on Objective 4 of the thesis, which applies the validated model from Objective 3, to estimate the climate change effect on grain yield and livestock population in smallholder MCLS of Ghana and Burkina Faso.

3.4.1 Study area

3.4.1.1 Climate

The climate for the reference locations in the communes of Obritenga province of Burkina Faso and the districts of the Upper East region of Ghana were the same as described under Chapter 3.2.1 (Table 4).

Table 4. Climate of the study areas in Burkina Faso and Ghana

Country	Communes/ district	Latitude (N)	Longitude (W)	Average annual rainfall (mm)	Mean temperature (°C) range
Burkina Faso	Loumbila	12° 50’	1° 39’		
	Ziniaré	12° 57’	1° 29’	650	23.0–33.0
	Zitenga	12° 73’	1° 31’		
Ghana	Kassena Nankana	10° 91’	1° 13’		
	Builsa North	10° 80’	1° 16’	927	25.5–29.9
	Bongo	10° 88’	0° 85’		

3.4.1.2 Soil

The characteristics of soils in the study areas (Table 5), were the same as described under chapter 3.2.3 described by Nachtergaele et al. (2023).

Table 5. Physico-Chemical properties of soil in the study areas of Burkina Faso and Ghana

Soil parameters	Burkina Faso (0 – 30 cm)	Ghana (0 – 30 cm)
Predominant soil type	Plinthosols	Lixisols
pH(H_2O)	5.9	6.3
[a]OCC (by weight)	0.50%	0.53%
[b]TEB (cmol kg^{-1})	4.5	4.0
[c]CEC (cmol kg^{-1})	5.0	4.0
Soil textural class	Sandy loam	Sandy loam

[a]**OCC** = organic carbon content, [b]**TEB** = total exchangeable bases, [c]**CEC** = cation exchange capacity

3.4.2 Datasets for climate analysis

Data on soil, crop and livestock were the same for baseline and future as described under chapter 3.3.2.2 to 3.3.2.4

3.4.2.1 Climate data

Climate data were obtained for the time slices 2020–2024 and 2025–2050 representing the baseline and future climate, respectively. Projections of future climate were obtained using Coupled Model Intercomparison Project Phase 6 (CMIP6) dataset available at 100 km spatial resolution and one shared SSP, namely, ssp585, for carbon emissions (IPCC, 2014). The future time-scale weather series and the corresponding projected carbon dioxide (CO_2) concentration, according to SSPs used in all crop model simulations without bias correction, are 380 as the baseline and 450 for ssp585. The GCM used in the current simulations was GFDL-ESM4: Geophysical Fluid Science Laboratory-Earth System Modelling (https://www.gfdl.noaa.gov/earth-system-esm4/). The

GFDL-ESM4 is described in detail by Krasting et al. (2018), and Dunne et al. (2020) and has been shown to have one of the best simulations over West Africa among all the models from CMIP6 (Agbor et al., 2023; Almazroui et al., 2020; Faye & Akinsanola, 2022).

3.4.3 Data analysis

To assess the effect of future climate projections on grain yield and livestock numbers of MCLS farmers in the study locations, simulations were conducted using the SIMPLACE simulation model. The weather data were replaced by the projected weather data of near-term (2025-2050) climate scenarios. Baseline grain yield and livestock number were compared with simulated grain yield and livestock number, respectively as projected by the selected GCM (GFDL-ESM4) for the near-time period. In addition, the impact of climate change on grain yield and livestock number were evaluated by calculating the relative change as following equation 11 and 12, respectively:

$$\Delta Yield = \frac{Yield_{Future} - Yield_{Baseline}}{Yield_{Baseline}} \ x \ 100 \qquad (11)$$

Where $\Delta Yield$ is the relative yield change

$Yield_{Future}$ is the yield for the climate scenarios

$Yield_{Baseline}$ is the yield for the baseline scenarios

$$\Delta Lnumber = \frac{Lnumber_{Future} - Lnumber_{Baseline}}{Lnumber_{Baseline}} \ x \ 100 \qquad (12)$$

Where $\Delta Lnumber$ is the relative change in livestock number

$Lnumber_{Future}$ is the livestock number for the climate scenarios

$Lnumber_{Baseline}$ is the livestock number for the baseline scenarios

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Environmental and management factors affecting greenhouse gas fluxes from soils in mixed crop-livestock systems– A meta-analysis

4.1.1 Research on MCLS and soil GHG fluxes

The meta-analysis incorporated 99 observations extracted from 21 studies published between 2013 and 2022 across two continents; North America and South America (Figure 4), meeting the established selection criteria (see section 3.1.1.2). Among these, 20 studies provided data on soil N_2O emissions, 14 on CH_4 emissions, and 7 on CO_2 emissions (Appendix 2). The dataset predominantly represented North and South America (Figure 1), reflecting the greater adoption and research focus on field-level (co-located) MCLS within these regions (Peterson et al., 2020). In contrast, MCLS practices in Africa, Europe, and Asia are more commonly implemented at the farm or regional scale (Chen et al., 2023; Peyraud et al., 2014; Rufino et al., 2021). In confirming this, a meta-analysis by Peterson et al. (2020) on yields in co-located MCLS revealed data exclusively from North America, South America, and Australia. Additionally, there has been a noticeable decline in the prevalence of MCLS in Europe and Asia. Across all farming systems; crop-only, livestock-only, and mixed farms, integrated systems account for just 10–20% of farms in Europe (Franzluebbers, Lemaire, et al., 2014; Garrett et al., 2020; Peyraud et al., 2014) and less than 10% in Asia (Garrett et al., 2020).

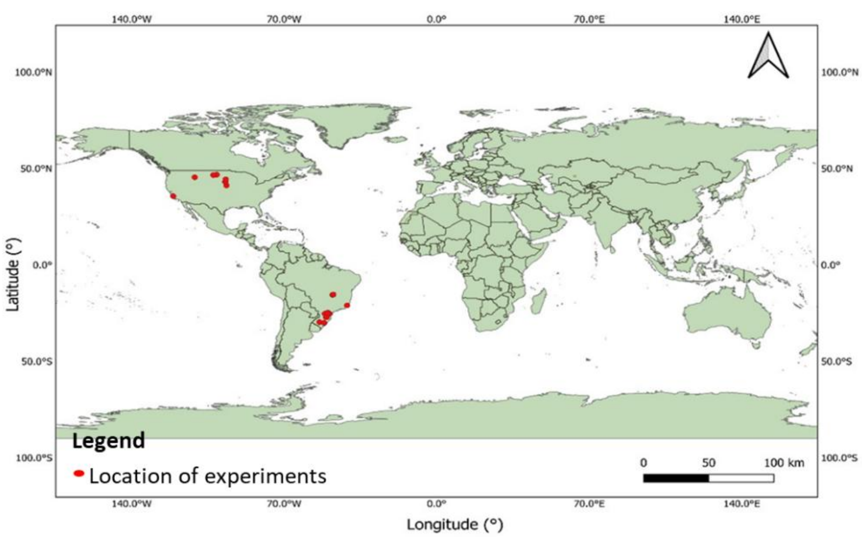

Figure 4. Distribution of MCLS experiments measuring GHGs emission included in our meta-analysis.

4.1.2 MCLS and GHGs: Overall effect

Our findings indicate that mixed crop-livestock systems (MCLS) had no significant impact on soil N_2O emissions compared to arable systems. Many of the studies on N_2O included in this analysis observed RR < 1 from integrated systems, most of the impacts were minor as compared to studies with RR > 1. In contrast, MCLS significantly elevated CH_4 and CO_2 emissions by 40% (CI: 13%–75%) and 38% (CI: 15%–62%), respectively (Figure 5), underscoring their substantial contribution to these greenhouse gases. On the other hand, the relative importance of variables influencing GHG emissions in MCLS, as shown in Figure 6, was ranked as follows: drainage class > stocking density > climate > N fertilizer amount > fertilizer type > soil texture > crop type > tillage > livestock type > MCLS type. The random forest model achieved a mean squared error of 0.82 for the test set.

MCLS contribute to enhanced ecosystem functioning, nutrient cycling (Szymczak et al., 2020), and improved farm-level socioeconomics, such as livelihood diversification and economic risk mitigation (Bell et al., 2014). However, their role in GHG emissions remains contentious. While N_2O emissions under MCLS showed a neutral effect compared to arable systems, CH_4 emissions increased significantly. This rise is likely due to the incorporation of livestock manure, a well-documented source of CH_4 flux (Iqbal et al., 2023; USEPA, 2021), and soil compaction caused by livestock trampling, which reduces aeration porosity (Piva et al., 2019; Ribeiro et al., 2020). Similarly, the increase in CO_2 emissions can be attributed to heightened microbial activity and carbon mineralization triggered by the addition of livestock manure. Manure not only introduces soil microbes but also stimulates microbial respiration, as supported by findings from Lecain et al. (2000) and Olaleye et al. (2020). The latter reported elevated CO_2 emissions under conditions of continuous heavy grazing compared to light grazing or ungrazed pastures, consistent with our observations.

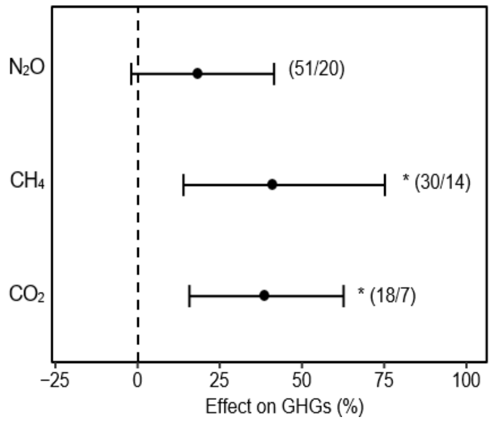

Figure 5. Overall effect of MCLS on cumulative/annual GHGs emissions relative to the unintegrated system.

NB: Number of observation/number of studies for each category appears in parentheses. Points represent the effect of MCLS on GHGs, with the GHG emissions from the paired arable systems denoted by the dashed vertical line. Error bars depict 95% bias-corrected-accelerated bootstrap confidence intervals. Asterisks (*) indicate a significant GHG response in MCLS compared to the arable system.

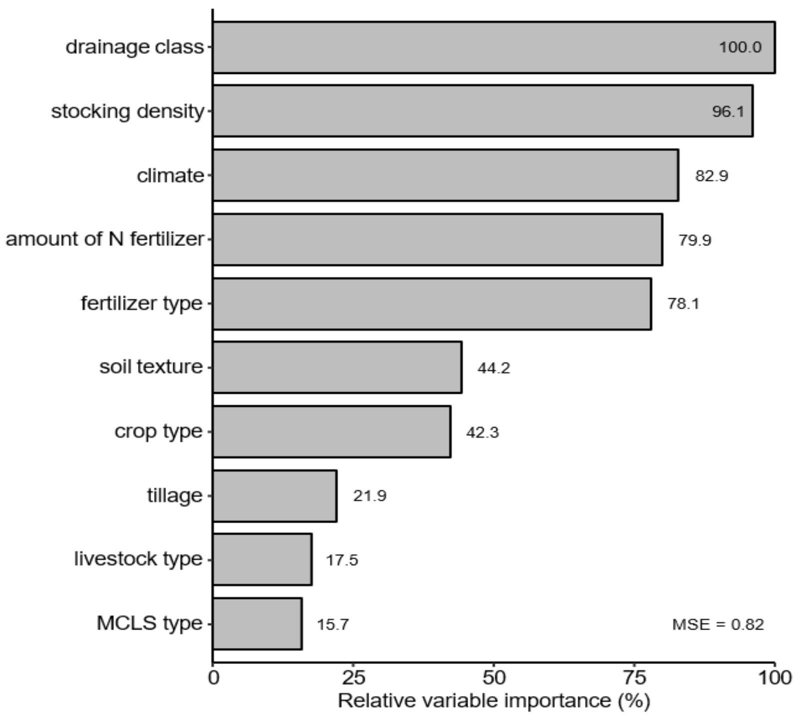

Figure 6. Relative variable importance ranking. The rankings are generated using a random forest permutation procedure, employing the effect size of MCLS relative to arable systems as the response variable

4.1.3 Effect of drainage class on GHGs emissions

Figures 7a–c illustrates the influence of drainage class on soil N_2O, CH_4, and CO_2 emissions in mixed crop-livestock systems (MCLS). Our findings show that poorly and imperfectly drained soils under MCLS significantly increased N_2O emissions by 38% (CI: 18%–63%) and 23% (CI: 1.9%–48%), respectively, compared to arable systems (Figure 7a). Similarly, MCLS under moderately well drained soils significantly increased CO_2 emission by 32% (CI:8%-58%) (Figure 7c). On the other hand, drainage class had no significant influence on CH_4 emissions under MCLS as compared to arable systems (Figure 7b).

These results align with existing evidence highlighting the critical role of drainage in regulating mineralization and denitrification processes (Kumar et al., 2014). The observed increase in N_2O emissions in poorly and imperfectly drained soils under MCLS can be attributed to several factors, including altered soil properties, drainage conditions, and nitrogen inputs from livestock. Elevated moisture levels in poorly drained soils likely enhance denitrification, leading to greater N_2O production (Venterea et al., 2008). Soil compaction, common in MCLS, creates anaerobic conditions favorable for N_2O generation during denitrification (Beare et al., 2009). Furthermore, the deposition of livestock urine and dung introduces additional water and labile nutrients, which further stimulate N_2O emissions (Cai et al., 2017).

4.1.4 Stocking density influence on GHGs emissions

Figures 7d–f present the effect sizes of stocking density on soil N_2O, CH_4, and CO_2 emissions under MCLS. Moderate and high stocking densities significantly increased N_2O emissions by 38% (CI: 14%–64%) and 23% (CI: 3%–48%), respectively, compared to arable systems (Figure 7d). Conversely, CH_4 emissions were 15% higher (CI: 7%–58%) under low stocking densities (Figure 7e), while CO_2 emissions showed no significant differences across all stocking densities in MCLS and arable systems (Figure 7f).

The observed sensitivity of N_2O and CH_4 emissions to stocking density variations suggests that these gases respond more strongly to changes in stocking rates than CO_2 (Figures 7d–f). The higher N_2O emissions at moderate and high stocking densities likely result from increased manure deposition, which elevates NH_4^+ and NO_3^- availability as substrates for microbial nitrification and denitrification processes, as noted by Yao et al. (2017). Interestingly, CH_4 emissions were unexpectedly higher at low stocking densities, a result contrary to prior studies linking high grazing intensities to increased soil compaction and anaerobic conditions that elevate CH_4 emissions (De Klein and Ledgard, 2005; Piva et al., 2014). The mechanisms behind elevated CH_4 emissions under low stocking densities remain unclear, but this finding diverges from earlier research suggesting reduced soil CH_4 uptake under high grazing pressures.

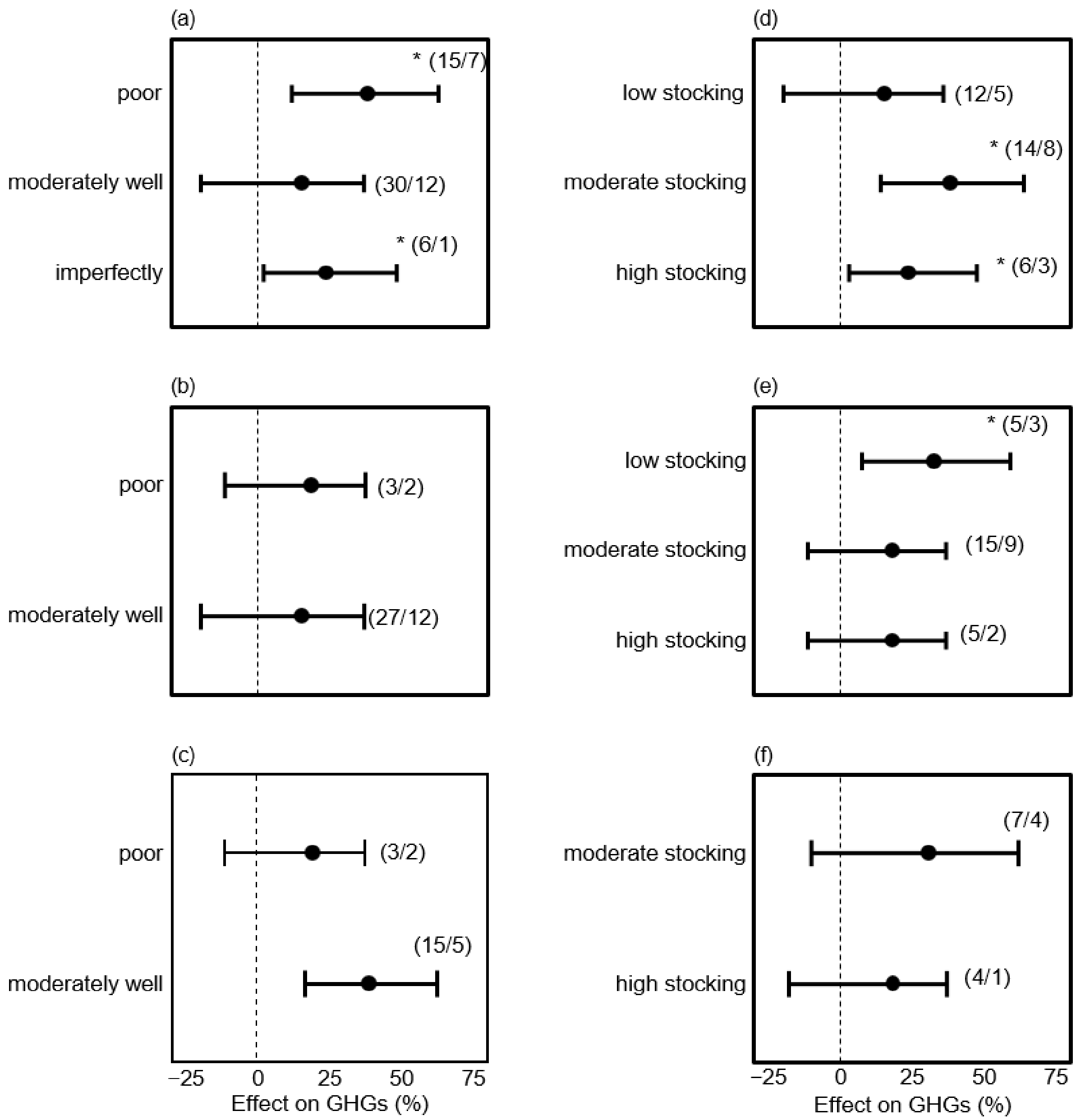

Figure 7. Effect of MCLS on cumulative/annual GHGs emission relative to arable system within drainage class for (a) N_2O, (b) CH_4, and (c) CO_2 and stocking density for (d) N_2O, (e) CH_4, and (f) CO_2.

NB: Number of observation/number of studies for each category appears in parentheses. Subgroup analysis excluded categories with fewer than three observations. Points represent the effect of MCLS on GHG, with the paired arable system GHG denoted by the dashed vertical line. Error bars depict 95% bias-corrected-accelerated bootstrap confidence intervals. Asterisks (*) indicate a significant GHG response in MCLS compared to the arable system.

4.1.5 Effect of climate on GHGs emissions

The effect sizes of climate on N_2O, CH_4, and CO_2 emissions from MCLS are presented in Figures 8a, 8b, and 8c. MCLS significantly increased N_2O emissions by 38% (CI: 13%–63%) in tropical climates and 44% (CI: 18%–72%) in temperate climates. However, no significant difference was observed in continental climates (32%, CI: -0.2%–60%) compared to arable systems (Figure 8a). For CH_4 emissions, significant increases were recorded in temperate (38%, CI: 14%–64%) and continental (36%, CI: 9%–63%) climates, while the effect size for tropical climates could not be determined due to insufficient data (n = 0) (Figure 8b). Across all climate categories, CO_2 emissions from MCLS were comparable to those from arable systems, indicating no significant differences (Figure 8c).

Precipitation and temperature emerged as pivotal factors influencing the observed trends in GHG emissions across climate zones. In tropical and temperate climates, the higher minimum temperatures (Tmin) and minimum precipitation levels (Pmin) likely extended the duration of anaerobic soil conditions, leading to elevated N_2O emissions. This aligns with previous findings by Pärn et al. (2018) and Barnard et al. (2005), who attributed higher N_2O emissions in these regions to increased microbial activity facilitated by warm, moist conditions. Additionally, tropical zones foster microbial nitrification and denitrification processes conducive to N_2O emissions (Xu-Ri et al., 2012).

Conversely, CH_4 emissions were significantly influenced by temperature variations, with temperate and continental zones exhibiting higher emissions than tropical zones. These results may be explained by the synergistic effect of livestock excretions (manure and urine) and cooler Tmin conditions, which create an optimal environment for methanogenic bacterial activity. Supporting studies by Cai et al. (2017) highlighted the abundance of methanogenic bacteria in animal manure as a key driver of CH_4 emissions. Similarly, prior research (Naser et al., 2007) demonstrated elevated CH_4 emissions in cool temperate and frigid regions compared to tropical and subtropical areas.

For CO_2 emissions, all climate zones displayed a neutral effect, suggesting that MCLS does not substantially influence soil CO_2 fluxes compared to arable systems. This consistency across climates may reflect a balance between increased microbial respiration due to manure inputs and other offsetting factors, such as soil carbon sequestration processes. In summary, the findings demonstrate that N_2O and CH_4 emissions are strongly influenced by climatic conditions, particularly temperature and precipitation, while CO_2 emissions remain unaffected across all climate zones.

4.1.6 Effect of fertilizer type on GHGs emissions

Significant increases in N_2O (23%, CI: 2% - 47%) and CH_4 (38%, CI: 15% - 61%) emissions were observed for nitrogen (N) fertilizer application in MCLS (Figures 8d and 8e). However, replacing N fertilizer with phosphorus (P) fertilizer, organic fertilizer, or no fertilizer resulted in no significant difference in N_2O and CH_4 emissions between MCLS and arable systems. Similarly, no notable differences in CO_2 emissions were observed across all fertilizer types (Figure 8f).

The observed increase in N_2O emissions aligns with the widely accepted hypothesis of a linear relationship between N application and N_2O flux. N-based fertilizers, such as urea and ammonium sulfate, intensify soil N_2O emissions by boosting nitrification and denitrification rates (Campanha et al., 2019; Plaza-Bonilla et al., 2018; Thomas et al., 2017). Manure, known for its high N mineralization rates (Akiyama et al., 2004), further compounds this effect, particularly within MCLS where its combination with N fertilizers elevates soil nitrogen levels. This synergistic effect has been documented in prior studies, such as Piva et al. (2014), who observed a significant surge in N_2O fluxes following urea application in both MCLS and purely arable croplands, though the increase was more pronounced in MCLS. Similarly, Shakoor et al. (2018) noted elevated N_2O emissions at higher levels of nitrogen application.

While upland soils typically emit minimal CH_4 (Singh et al., 2020b), our results reveal that mineral N fertilizer application increased CH_4 emissions in MCLS compared to arable systems. This could be attributed to livestock trampling in MCLS, which increases soil bulk density, reduces porosity, and diminishes aeration. The reduced aeration may suppress methanotrophic activity, which is responsible for oxidizing CH_4 into CO_2 under aerobic conditions (Saggar et al., 2008). Additionally, Zanatta et al. (2010) observed CH_4 emission peaks occurring 4–6 days after N fertilizer application, further highlighting the interplay between fertilizer management and soil properties.

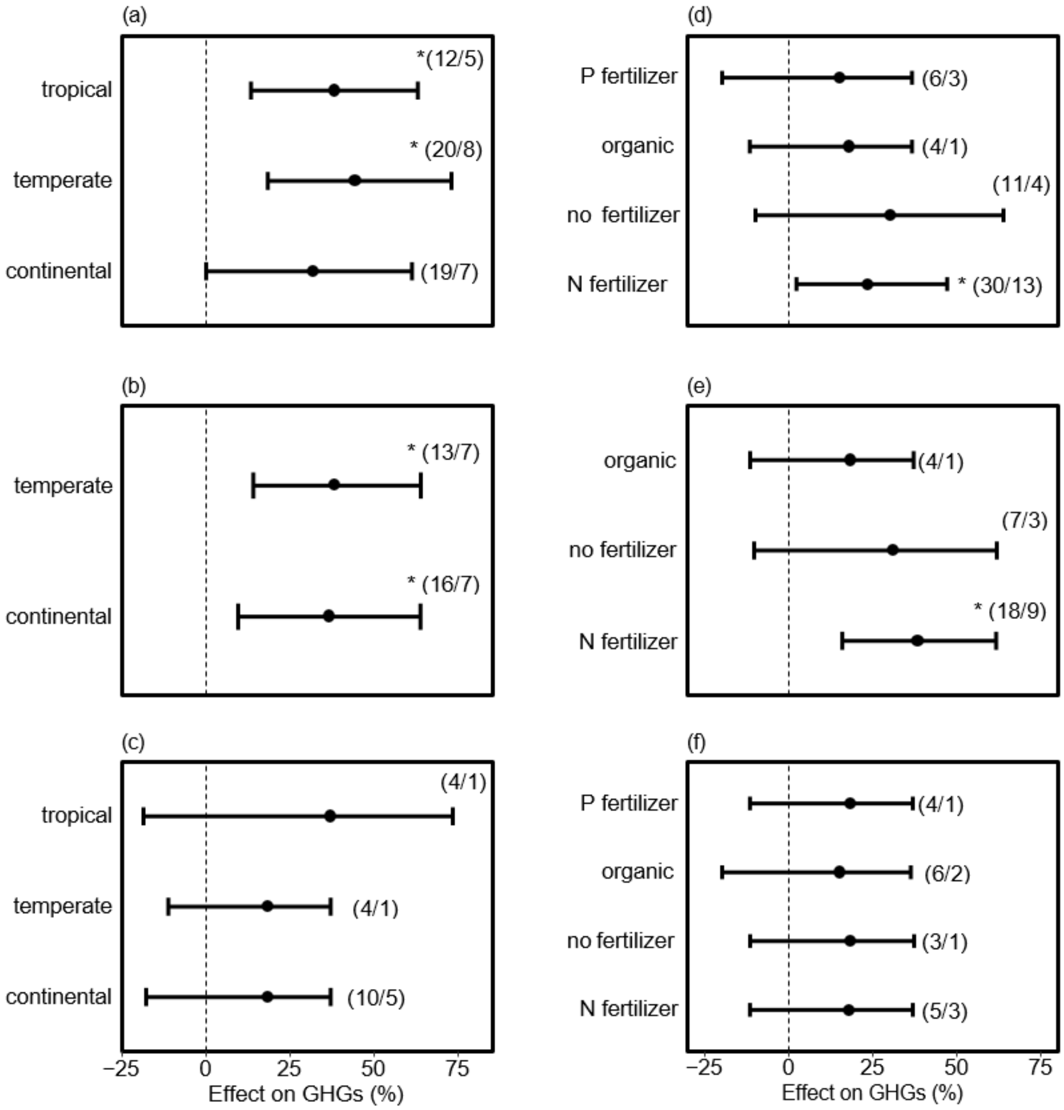

Figure 8. Effect of MCLS on cumulative/annual GHGs emission relative to arable system within climate categories for (a) N_2O, (b) CH_4, and (c) CO_2 and fertilizer categories for (d) N_2O, (e) CH_4, and (f) CO_2.

NB: Number of observation/number of studies for each category appears in parentheses. Subgroup analysis excluded categories with fewer than three observations. Points represent the effect of MCLS on GHG, with the paired arable system GHG denoted by the dashed vertical line. Error bars depict 95% bias-corrected-accelerated bootstrap confidence intervals. Asterisks (*) indicate a significant GHG response in MCLS compared to the arable system.

4.1.7 Effect of mineral N fertilizer amount on GHGs emissions

Both low and high rates of N application significantly influenced N_2O and CH_4 emissions, while CO_2 emissions remained unaffected across all rates (Figures 9a, 9b, and 9c). Specifically, N_2O emissions increased significantly under both low (33%, CI: 13%–55%) and high (38%, CI: 16%–62%) N application rates (Figure 9a). In contrast, only the high N application rate significantly elevated CH_4 emissions by 31% (CI: 4%–57%) (Figure 9b). For CO_2 emissions, neither low (30%, CI: -9%–66%) nor high (31%, CI: -10%–62%) N application rates showed significant differences between MCLS and the arable system (Figure 9c).

The relationship between N application rates and greenhouse gas emissions is well-documented, with a linear increase in N_2O emissions corresponding to rising N fertilizer rates (Dobbie and Smith, 2003; Yu, 2011). The Intergovernmental Panel on Climate Change (IPCC) suggests that 1% of applied nitrogen is emitted as N_2O. Our meta-analysis confirms this trend, with N_2O emissions from MCLS increasing almost linearly with N application rates compared to the arable system (Figure 9a). The increased N_2O emissions in MCLS can be attributed to the higher availability of NH_4^+ and NO_3^- derived from both mineral fertilizers and livestock manure which serve as substrates for nitrification and denitrification processes. Animal manure has been reported to contain NH_4^+ concentrations ranging from 147 to 4638 mg kg^{-1} and NO_3^- concentrations from 3.97 to 120 mg kg^{-1} (Kim et al., 2019). This elevated nitrogen availability in MCLS soils likely drives the observed differences in N_2O emissions between MCLS and arable systems.

CH_4 emissions were significantly higher under high N application rates (>120 kg N ha^{-1}) in MCLS compared to arable systems (Figure 9b). This increase may stem from the combined effects of mineral N fertilizer and manure deposition, which enhance methanogen activity. Nitrogen is known to stimulate methanogens, which convert organic matter into CH_4 (Bodelier and Laanbroek, 2004). Additionally, ammonium in the soil competes with CH_4 for active methane monooxygenase, resulting in higher CH_4 emissions in ammonium-rich soils (Bédard and Knowles, 1989; Hütsch, 1998). Interestingly, the relationship between nitrogen and CH_4 emissions is not universally consistent. Some studies suggest that nitrogen fertilizer can suppress CH_4 production, as nitrate reduction intermediates (e.g., nitrite, NO, and N_2O) are toxic to methanogens (Yao et al., 2012). However, Hütsch et al. (1993) proposed that such inhibitory effects may take several years of sustained fertilizer application (>7 years) to manifest.

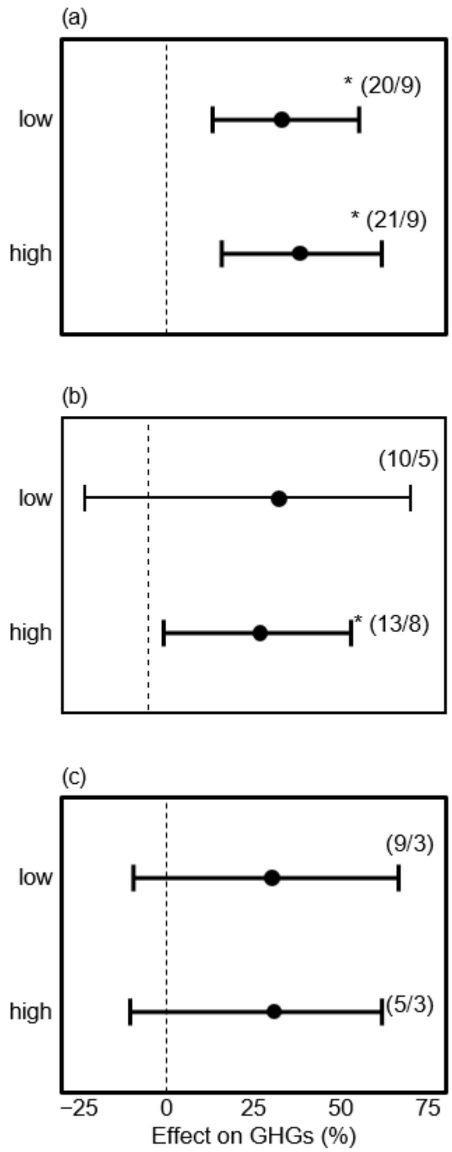

Figure 9. Effect of MCLS on cumulative/annual GHGs emission relative to arable system within mineral N fertilizer rate categories for (a) N_2O, (b) CH_4, and (c) CO_2.

NB: Number of observation/number of studies for each category appears in parentheses. Subgroup analysis excluded categories with fewer than three observations. Points represent the effect of MCLS on GHG, with the paired arable system GHG denoted by the dashed vertical line. Error bars depict 95% bias-corrected-accelerated bootstrap confidence intervals. Asterisks (*) indicate a significant GHG response in MCLS compared to the arable system.

4.1.8 Effect of soil textural classes on GHGs emissions

From our results, MCLS under sandy soils significantly increased N_2O emissions by 38% (CI: 15% to 61%), whereas loam (17%, CI: -4% to 42%) and clay (18%, CI: -11% to 37%) did not show any significant difference between MCLS and arable systems (Figure 10a). On the other hand, loamy soils had no significant influence on CH_4 emissions under MCLS as compared to arable systems (Figure 10b). Conversely, when MCLS was implemented on clay soils, CH_4 emissions significantly increased by 33% (CI: 13% to 55%) relative to the arable system (Figure 10b). Confidence intervals could not be generated for sandy soils due to the small number of observations (n = 2) realised for studies on CH_4 emission. Moreover, sandy soils under MCLS as compared to arable systems significantly contributed to a higher CO_2 emission of 36% (CI: 9% to 63%). In contrast, the effect of loamy soils (18%, CI: -18% to 37%) on CO_2 emission was not significantly different between MCLS and arable systems (Figure 10c). Confidence intervals were unable to be computed for clay soils due to lack of CO_2 emission data in the studies incorporated into our analysis

The cation exchange capacity (CEC) significantly impacts N_2O emissions by regulating the availability of ammonium in the soil. Among the textural classes analyzed in our meta-analysis, sandy soils demonstrated the lowest CEC values (CUCE, 2007). As a result, the greater availability of soil ammonium-N, derived from both N-based mineral fertilizers and livestock manure in sandy soils under MCLS, likely contributes to increased N_2O production. De Visscher et al. (1998) reported that higher NH_4^+ inputs in soils with low CEC are associated with elevated N_2O emissions. Similarly, Fernando et al. (2005) investigated NH_4^+ adsorption from manure and ammonium sulfate in soils with differing CEC levels, finding that clay-rich soils had NH_4^+ adsorption maxima of 1000 and 909 mg NH_4^+ kg^{-1} soil for manure and $(NH_4)_2SO_4$ treatments, respectively. In contrast, sandy soils exhibited lower NH_4^+ adsorption maxima of 625 mg NH_4^+ kg^{-1} for manure and 217 mg NH_4^+ kg^{-1} for $(NH_4)_2SO_4$. These findings align with our study.

Clayey soils within MCLS showed significantly higher CH_4 emissions (Figure 10b). Similar results have been reported in studies examining fine-textured soil effects on CH_4 emissions (Ball, 2013; Shakoor et al., 2021). According to Islam and Weil (2000), fine-textured soils contain more fine pores, which foster anaerobic conditions. Dutaur and Verchot (2007) corroborated this, noting that such conditions in fine pores encourage CH_4 emissions. Additionally, manure application introduces methanogenic bacteria while simultaneously depleting oxygen levels, thereby creating anaerobic conditions conducive to CH_4 production (Jarecki et al., 2008). This effect has been observed to trigger immediate increases in CH_4 fluxes (Chan and Parkin, 2001; Sherlock et al., 2002). The combination of methanogenic bacterial inoculation via manure and the prevalence of anaerobic conditions in fine-pored clay soils likely results in elevated CH_4 emissions in MCLS.

In the case of CO_2 emissions, sandy soils in MCLS exhibited the highest levels compared to the arable system. This can be attributed to the inherent properties of sandy soils, which are characterized by larger particle sizes and increased macropores that influence gas transport (Sadeghi et al., 2018; Teixeira et al., 2012). Additionally, grazing livestock excrement, including manure and urine, enhances microbial activity by providing organic carbon for decomposition. This process, driven by heterotrophic microbial communities, further amplifies CO_2 emissions. These findings are consistent with Mangalassery et al. (2014), who highlighted that higher porosity in sandy soils facilitates water and air movement, enhancing aerobic microbial respiration and organic matter mineralization, leading to increased CO_2 flux.

4.1.9 Effect of crop type on GHGs emissions

MCLS had no effect on N_2O emission for cereals, legumes, and oil seed crops (Figure 10d). However, when grapes were included, MCLS had a significantly positive (36%) effect on N_2O emission relative to the arable system (Figure 10d). Alternatively, cereals in MCLS significantly increase CH_4 emission relative to the arable system by 36% (CI: 14% to 59%) (Figure 10e). Conversely, there was no difference between MCLS and arable systems for CH_4 and CO_2 emission when the crop was either a legume, oil seed, or grape (Figure 10e and f).

Research shows that GHG emissions differ across crop types due to variations in input usage and nutrient-use efficiencies. Even within the same crop type, emissions can vary significantly between farms, depending on agronomic practices. Optimizing fertilizer management through the 4 R's: right source, right rate, right time, and right place, is essential for maximizing yield and minimizing soil GHG emissions across various crop systems (Snyder, 2017). MCLS combined with grape production in vineyards demonstrated significantly higher N_2O emissions (Figure 10a). Several management-related factors may explain this trend. All MCLS vineyard plots in the study received organic fertilizers, particularly compost. Supporting this observation, Longbottom and Petrie (2015) reported a substantial increase in N_2O emissions in compost-treated vineyards, with emissions peaking 13–19 days after application, reaching levels up to 40 times those of the control. Additionally, optimal nitrogen application in vineyards through fertigation is recommended during active root growth phases, such as just before flowering and harvest (Comas et al., 2010). Nitrogen applications outside these periods could lead to elevated N_2O emissions (Longbottom and Petrie, 2015). Furthermore, grapevines are often cultivated in soils with low sorption capacities (Niemiec et al., 2021), increasing nitrogen availability for nitrifying bacteria. This aligns with our findings of higher cumulative N_2O emissions in MCLS vineyards.

For cereals within MCLS, the meta-analysis revealed significantly higher CH_4 emissions compared to cereals in arable systems (Figure 10b). Crop type played a critical role in influencing soil CH_4 emissions. For instance, both maize and paddy fields are well-documented sources of CH_4 fluxes (Shakoor et al., 2021; Wu et al., 2023). However, among the two cereals, rice is particularly recognized for its substantial CH_4 contributions (Shang et al., 2011). However, the cereals studied in MCLS here were predominantly maize and wheat. The conflicting results suggest that generalizing crop-type impacts on CH_4 emissions is premature due to the complex interplay of factors such as microbial composition, soil nitrogen availability, and variations in soil aeration and porosity (Bodelier and Laanbroek, 2004; Guardia et al., 2016).

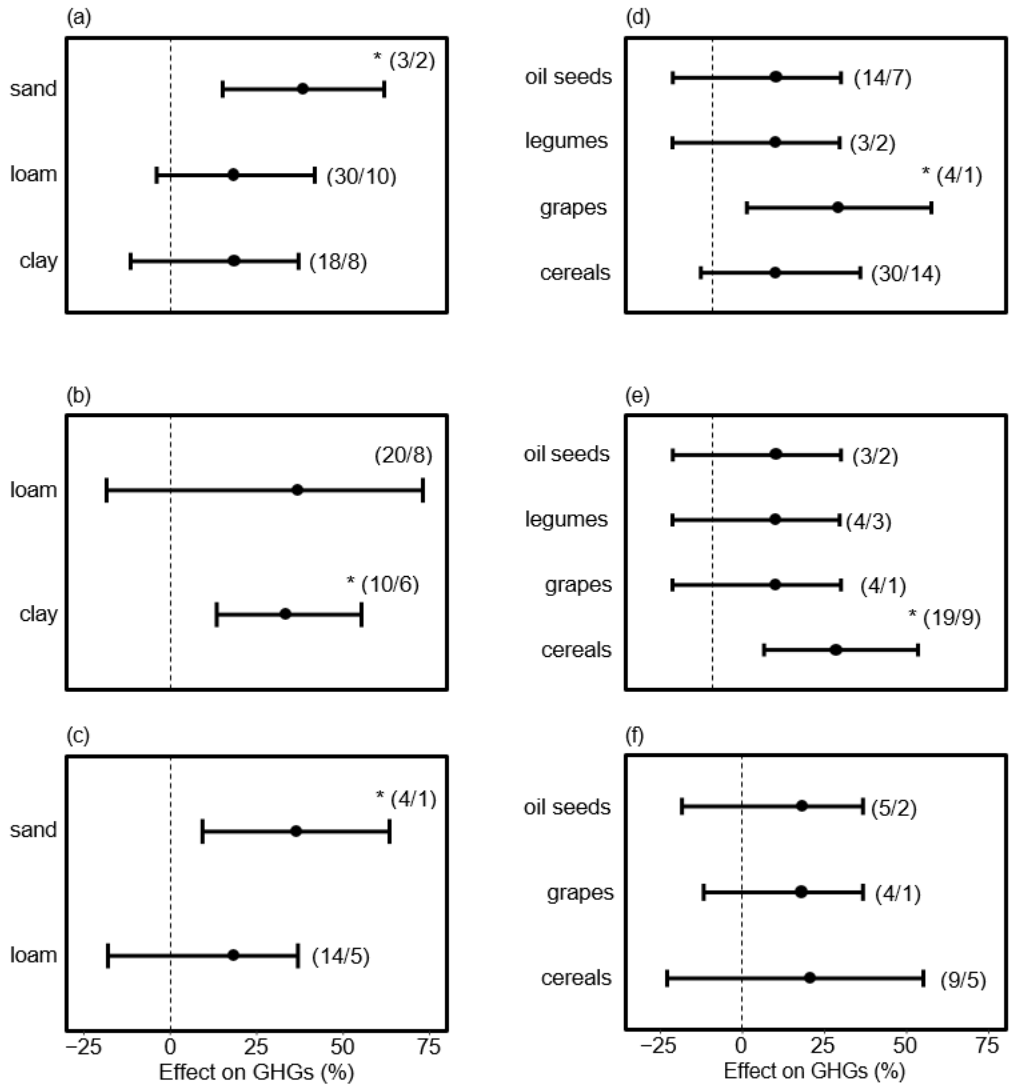

Figure 10. Effect of MCLS on cumulative/annual GHGs emission relative to arable system within soil texture categories for (a) N_2O, (b) CH_4, and (c) CO_2 and crop type for (d) N_2O, (e) CH_4, and (f) CO_2.

NB: Number of observation/number of studies for each category appears in parentheses. Subgroup analysis excluded categories with fewer than three observations. Points represent the effect of MCLS on GHG, with the paired arable system GHG denoted by the dashed vertical line. Error bars depict 95% bias-corrected-accelerated bootstrap confidence intervals. Asterisks (*) indicate a significant GHG response in MCLS compared to the arable system.

4.1.10 Effect of tillage on GHGs emissions

Our results showed that, between MCLS and arable systems, conventional tillage had no significant effect on soil N_2O, CH_4, and CO_2 emission, whereas with exception of CO_2 emission, conservation tillage increased them significantly (Figure 11a, and b). However, the magnitude of N_2O (43%) was larger than CH_4 (26%).

Conservation tillage methods, such as minimum or no-till, are known to improve soil quality (Lingling et al., 2014), increase soil carbon and nitrogen (Lazcano et al., 2022), and boost crop yields (Pittelkow et al., 2015). However, their effect on greenhouse gas (GHG) emissions is inconsistent, with studies reporting both increased (Pandey et al., 2013; Yao et al., 2013) and decreased emissions (Rutkowska et al., 2018; Yeboah et al., 2016) compared to conventional tillage. Our meta-analysis revealed that conservation tillage in MCLS significantly increased N_2O and CH_4 emissions compared to arable systems using the same practices.

Higher N_2O fluxes in MCLS with conservation tillage may result from enhanced soil properties due to manure incorporation (Iqbal et al., 2023) and conservation tillage itself (Alhassan et al., 2021). These practices improve soil structure, moisture retention, and organic matter, promoting conditions such as increased water-filled pore space, which drive N_2O emissions (Dobbie and Smith, 2003). Additionally, N_2O emissions correlate positively with soil temperature and moisture (Trujillo-Tapia et al., 2008) and are influenced by stimulated nitrification and denitrification processes in moist soils (Davidson and Swank, 1986). On the other hand, CH_4 emissions are affected by tillage (Alhassan et al., 2021; Shakoor et al., 2021) and livestock trampling (Ambus et al., 2018). Conservation tillage combined with grazing-induced soil compaction increases bulk density, reduces pore space, and fosters anaerobic conditions (Bayer et al., 2012). These factors inhibit methanotrophs and enhance CH_4 emissions through anaerobic decomposition of soil organic matter (Álvaro-Fuentes et al., 2008; Plaza-Bonilla et al., 2014).

4.1.11 Effect of livestock type on GHGs emissions

MCLS with small ruminants showed significantly higher N_2O (52%) and CH_4 (42%) emissions compared to arable systems, while CO_2 emissions (31%, CI: -3% to 61%) were not significantly different (Figure 11d, e, and f). However, when small ruminants were replaced with cattle, no significant differences were observed in N_2O (30%, CI: -10% to 63%), CH_4 (31%, CI: -10% to

61%), or CO_2 (15%, CI: -20% to 36%) emissions between integrated and arable systems (Figure 11d, e, and f).

Consistent with our meta-analysis (Figure 11d, e, and f), sheep excrement significantly increases N_2O and CH_4 emissions from agricultural soils (Zhao et al., 2021). This is due to differences in manure decomposition rates linked to livestock digestive systems, even with the same diet (Schlecht et al., 1998). Sheep dung decomposes slower than cattle dung due to its pelletized form, which resists fragmentation (Souto et al., 2005), potentially reducing the availability of active organic substances and mineral N. However, sheep manure contains higher nutrient concentrations, which are more evenly distributed (Bakker et al., 2004) and provide a steady nitrogen source for nitrifying bacteria, increasing cumulative N_2O emissions in MCLS. Studies also report higher N levels in sheep manure compared to cattle (Shriver et al., 2003; Valdés-Correcher et al., 2019).

Methane (CH_4) emissions from manure are largely influenced by the animal species, the composition and digestibility of their feed, and the microbial populations in their rumen and digestive tracts (Sejian et al., 2016). Wan et al. (2021), using the Shannon diversity index, reported greater microbial community diversity in sheep manure compared to cattle manure. Grazing animals also play a critical role in removing plant biomass and cycling nutrients back into the soil through dung and urine (Güsewell et al., 2005). Among livestock, feed quality significantly determines the nutrient content of manure returned to the soil. Small ruminants, such as sheep, tend to favor plants with higher nutritional value compared to cattle (Valdés-Correcher et al., 2019). In our meta-analysis, leguminous crops, such as cowpea and common bean, emerged as highly nutritious and preferred livestock fodder (Asibuo et al., 2008; Usman et al., 2013). However, these crops have been linked to increased methane production in livestock. Ansah et al. (2021) documented significantly higher CH_4 emissions in rams fed cowpea and groundnut, while Bamualim et al. (2008) highlighted that forage feeds high in crude fiber exacerbate methane emissions. Similarly, studies have shown that cowpeas and groundnuts have higher crude fiber content compared to crops like maize, wheat, and rice (Ibrahim et al., 2006; Jeremiah et al., 2015). These findings explain the elevated CH_4 emissions associated with sheep in our study, attributed to their distinct feeding preferences and the composition of their diets, as supported by these observations.

4.1.12 Effect of MCLS type on GHGs emissions

Our result revealed that different MCLS types had similar GHGs emissions between integrated and arable systems, except for forage rotation systems, where grazing of forages contributed to significantly higher N_2O (46%), CH_4 (33%) and CO_2 (31%) emissions than arable systems; no forage grazing controls (Figure 11g, h and i). Consequently, In a 5-year crop rotation experiment involving 3 years of alfalfa followed by wheat and barley, N_2O emissions were reported to be twice as high as those observed in a corn-wheat-corn-wheat-barley rotation system (Asgedom and Kebreab, 2011). Similarly, in a 24-year rotation study, Ross et al., (2008) compared three systems: (1) a continuous annual grain system, (2) a rotation involving faba bean, red clover, and alfalfa with manure, and (3) a continuous perennial grass-legume forage system supplemented with 18 kg N ha^{-1} $year^{-1}$ of fertilizer and white clover (Trifolium repens). Nitrogen losses to the atmosphere were measured at 4 kg N ha^{-1} $year^{-1}$ for the continuous annual grain system, 28 kg N ha^{-1} $year^{-1}$ for the rotation, and 24 kg N ha^{-1} $year^{-1}$ for the continuous perennial grass-legume forage system. These findings suggest that rotational forage systems, depending on the sequence and type of grazed forage crops, can function either as a source or sink of N_2O emissions.

On the other hand, (Abagandura et al., 2019) found no significant impact of crop rotational diversity on CH_4 flux. Similarly, Behnke et al. (2018) observed that a corn-soybean rotation produced CH_4 fluxes comparable to those of continuous corn or soybean systems, even after 17 years of rotation. However, studies by Ozlu and Kumar (2018) and Lee et al. (2018) highlight that soil's role as a CH_4 source or sink depends on the balance between CH_4-releasing microorganisms, which thrive under anaerobic conditions, and CH_4-consuming microorganisms, which are more active under aerobic conditions.

The soil CO_2 flux results suggest that forage rotation within a MCLS may lead to increased soil CO_2 emissions. In an MCLS experiment, Tracy and Zhang (2008) observed higher SOC concentrations in integrated crop–oat-pasture systems compared to a continuous corn system. It is plausible that in our study, the surplus SOC in the surface layers of forage rotation under MCLS provided additional substrates for soil microorganisms to respire. Likewise, the inclusion of multiple cover crops in rotation with corn and sorghum resulted in higher CO_2 emissions compared to cases with no cover crop in both corn and sorghum (Acharya et al., 2022). This was attributed to the increased total soil respiration (heterotrophic + root) induced by multiple cover crops. It is well-documented that plant root respiration can contribute anywhere from 7% to 90% of the total soil respiration, contingent on factors such as growth stage, vegetation type, and soil conditions (Hanson et al., 2000; Larionova et al., 2006).

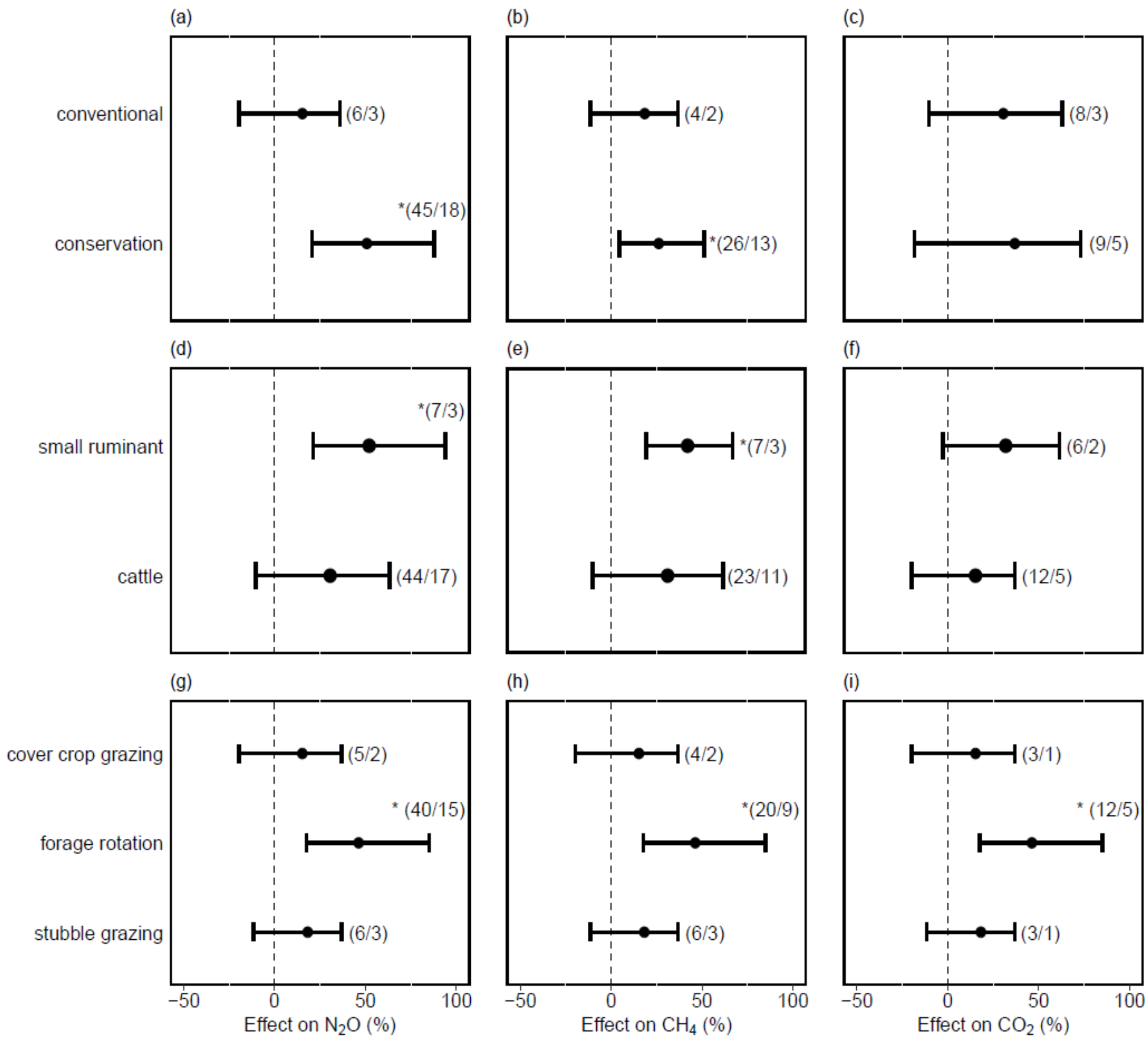

Figure 11. Effect of MCLS on cumulative/annual GHGs emission relative to arable system within tillage categories for (a) N_2O, (b) CH_4, and (c) CO_2; livestock categories for (d) N_2O, (e) CH_4, and (f) CO_2 and MCLS type for (g) N_2O, (h) CH_4, and (i) CO_2.

NB: Number of observation/number of studies for each category appears in parentheses. Points represent the effect of MCLS on GHG, with the paired arable system GHG denoted by the dashed vertical line. Error bars depict 95% bias-corrected-accelerated bootstrap confidence intervals. Asterisks (*) indicate a significant GHG response in MCLS compared to the arable system.

4.2 Impact of fertilizer applications on grain and vegetable crops in smallholder Mixed Crop-Livestock systems (MCLS) in Burkina Faso and Ghana.

4.2.1 Effect of fertilizer source on yields

With the exception of peanut and soybean yields in Ghana, fertilizer source significantly influenced grain yields in both countries (Fig. 12a and b). In Burkina Faso, 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 (Fig 12a). While the yield for cowpea under chemical fertilizer was greater, it was not significantly different from the yield obtained with the combined fertilizer application. For grain crops in Ghana, 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. In contrast, rice showed a response of 2685 kg ha^{-1} when chemical fertilizer was applied alone. Wei et al. (2016), 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. These findings are consistent with our findings. However, in Ghana 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. 12b). Nonetheless, the yield advantage remained below the national average yield for millet (1500 kg ha^{-1}) and cowpea (1670 kg ha^{-1}) (MoFA, 2022).

On the other hand, 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}) in Burkina Faso. Conversely, when chemical fertilizer was applied alone, tomato produced the highest ($P < 0.05$) fruit yield of 16,075 kg ha^{-1}. (Fig. 12c). Similarly, in Ghana, 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. 12d). The increased in fruit yield may be due to the availability of N, P, K and also the supply of organic matter by manure application. Khalid et al. (2014) and Geremew et al. (2019) also observed similar advantages on tomato fruit yields with combined manure and chemical fertilizer applications, and attributed the positive effect to improved soil nutrient status.

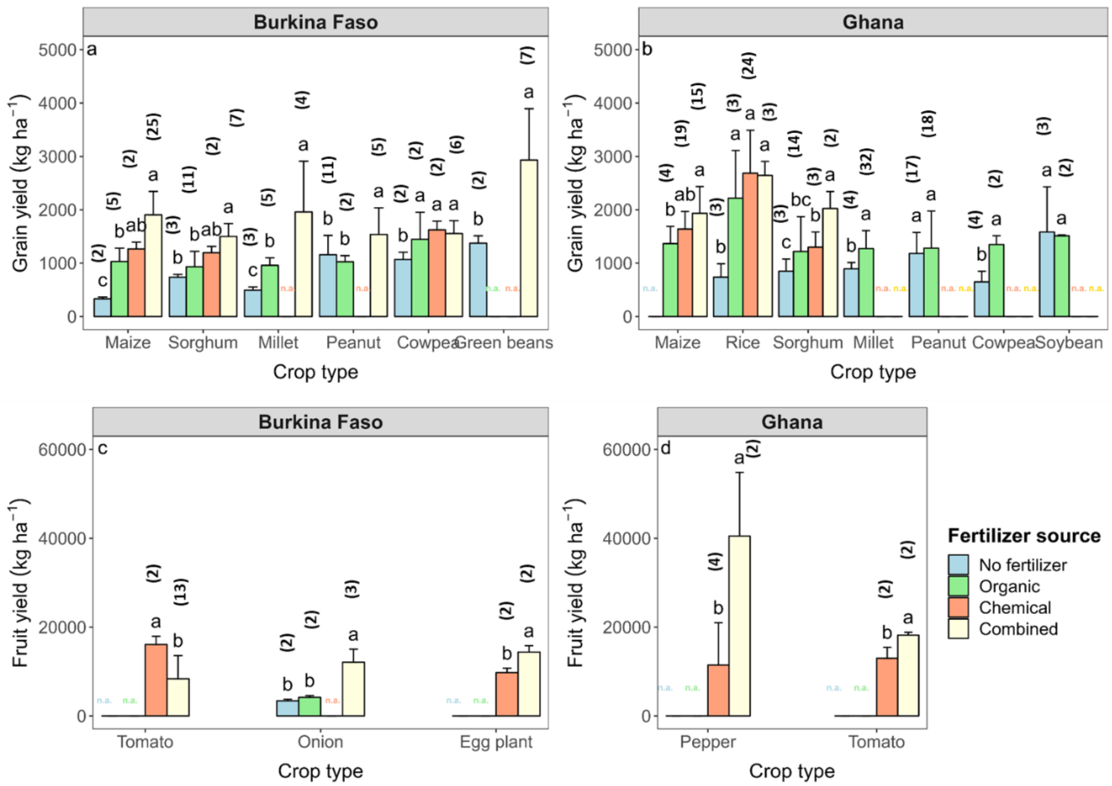

Figure 12. The effect of fertilizer source on grain (a – b) and fruit (c – d) yield in Burkina Faso and Ghana, respectively.

NB: 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.

4.2.2 Effect of fertilizer placement on yields

Figure 13 illustrates the impact of fertilizer placement methods on grain and fruit yields. In Burkina Faso, the furrow method of fertilizer application, when utilized, led to either significantly higher ($p < 0.05$) or numerically greater grain and fruit yields compared to broadcasting and side placement methods (Fig. 13a and c). The lower yields associated with broadcast and side placement methods 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. In Ghana, grain yields showed no significant response to different fertilizer placement methods (Fig. 13b). However, for vegetable crops, fertilizer placement methods significantly influenced yields. Side placement resulted in the highest fruit yields, with an average increase of 40% for tomatoes and 398% for peppers compared to broadcasting (Fig. 13d). The significantly higher fruit yields that were 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).

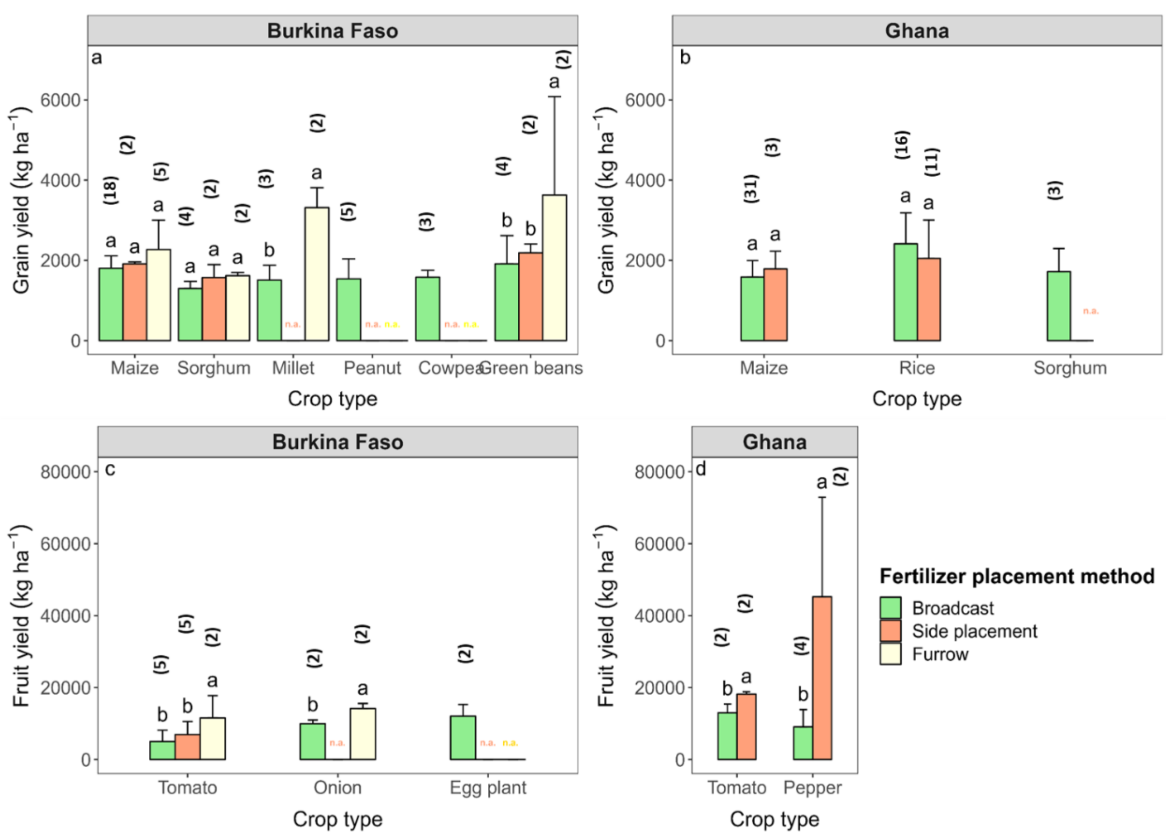

Figure 13. The effect of fertilizer placement method on grain (a – b) and fruit (c – d) yield in Burkina Faso and Ghana, respectively.

NB: 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.

4.2.3 Effect of fertilizer application timing on yields

The effects of the timing of chemical fertilizer and manure application are shown in Figures 14 and 15, 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% (Figure 14a and c). Conversely, late application of chemical fertilizer significantly increased ($p < 0.05$) millet yield by 78% (Figure 14a). In Ghana, no significant yield response was observed for grain crops under the different timing of chemical fertilizer application (Figure 14b). 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}. It is noteworthy that only a few crops showed significant responses to the timing of chemical fertilizer application, and even among these, the results did not consistently support the optimal timing. For instance, sorghum demonstrated better yields with late fertilizer application. Several factors could explain this observation. Marenya and Barrett (2009) highlighted that inorganic fertilizer is less effective on farmers' fields with low soil organic matter, irrespective of application timing. Additionally, challenges related to fertilizer application methods (broadcasting and side placement) observed in the study area, such as heavy rainfall or a sudden dry spell immediately after fertilization, may have diminished the effectiveness of precise timing. Genotypic variations also play a significant role in crop response to fertilization. For example, Ganyo et al. (2019) found that in the Sudano-Sahelian climate of Senegal, long-cycle sorghum genotypes benefited more from late fertilization compared to short-cycle varieties.

On the other hand, the timing of manure application had a significant impact on grain and vegetable crops in Burkina Faso, 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 (Figure 15a and c). 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 pepper fruit yield by 238% compared to early (optimum) manure application (Figure 15b and d). The varying responses to manure application timing can 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). Sileshi et al. (2017) noted that the rate of nitrogen (N) release over time differs depending on the animal source. For instance, 32%, 75%, and 90% of the N in manure from cattle, poultry, and pigs, respectively, becomes available during the first year of application (Eghball et al., 2002). These factors provide a plausible explanation for the observed variations in the effects of manure application timing in this study.

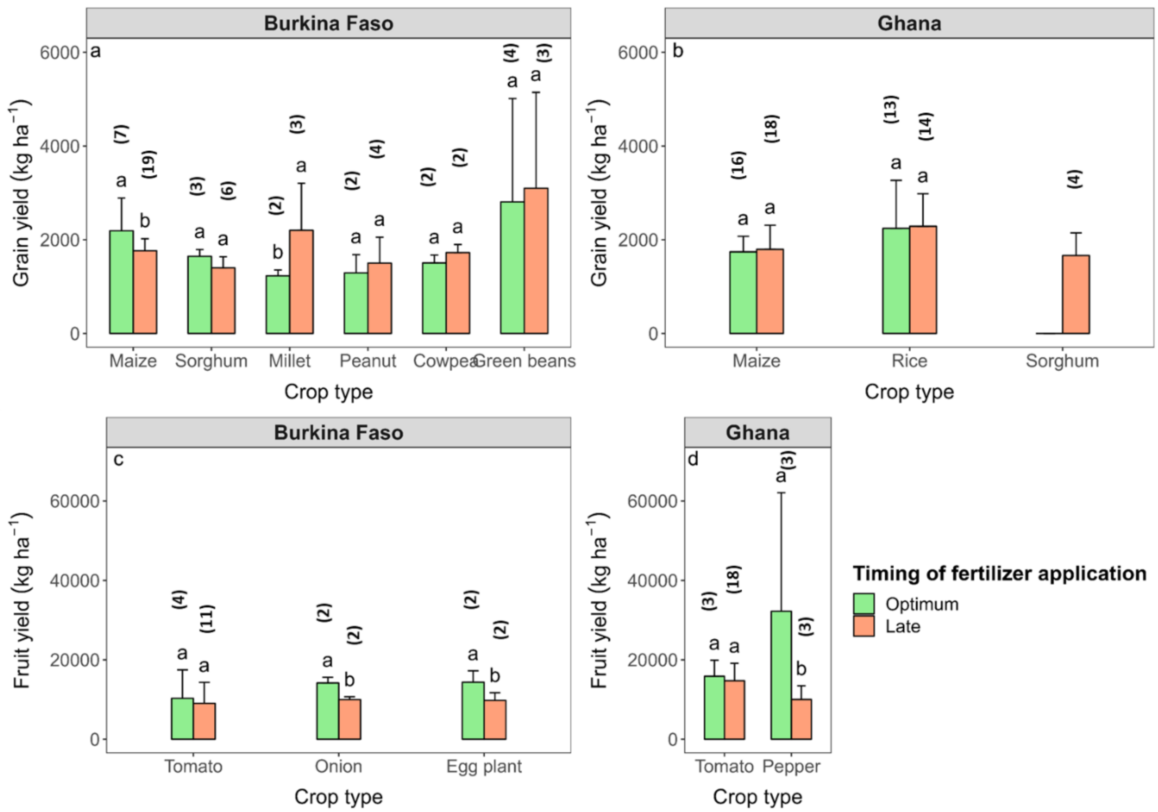

Figure 14. The effect of timing of chemical fertilizer application on grain (a – b) and fruit (c – d) yield in Burkina Faso and Ghana, respectively.

NB: 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.

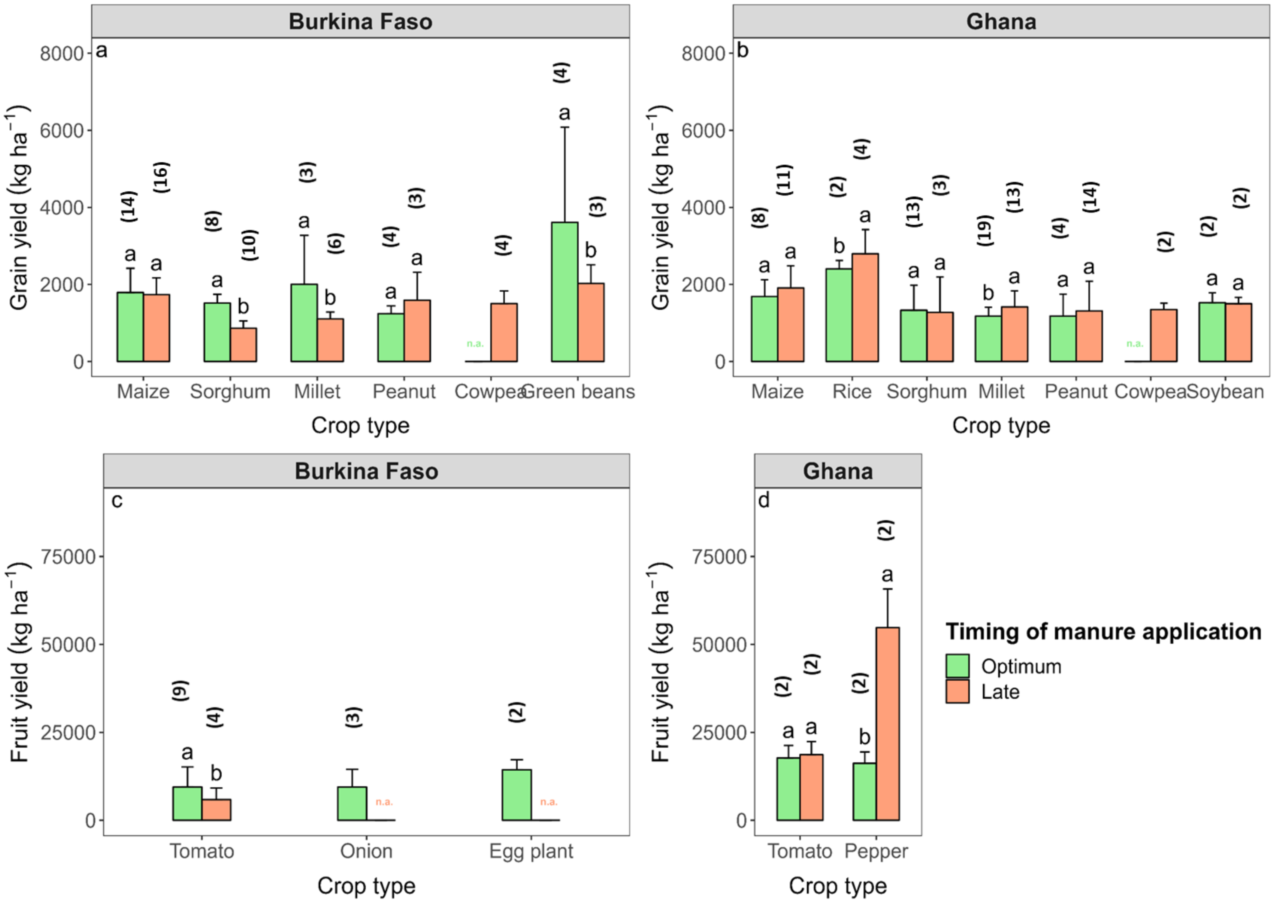

Figure 15. The effect of timing of manure application on grain (a – b) and fruit (c – d) yield in Burkina Faso and Ghana, respectively.

NB: 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.

4.2.4 Effect of applied N fertilizer on yields

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. Similarly, for Ghana, grain crops such as rice, sorghum, millet, and cowpea showed a significant response to the rate of nitrogen (N) applied (Figure 16b). Applying N at the recommended rate resulted in higher ($p<0.05$) grain yields compared to the low N application rate (Figure 16b). Although the recommended N application did not result in significant differences for other grain crops, it generally showed a tendency to increase yields. The variation of grain yield response patterns between crop types and countries 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 Figure 3, support this assertion. Similarly, in exploring the causes of poor crop responses to applied N on African soils, (Sileshi 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). However, due to the lack of data on the recommended N rate for onion and eggplant (in Burkina Faso) and tomato (in Ghana), formal statistical testing between recommended and low N rates was not feasible (Figure 16c).

Figure 17 highlights that manure was the primary source of nitrogen (N) in MCLS. However, in this study, the N content of manure was estimated as 1.6% of the total dry matter applied, which may not accurately represent the actual N content. Chikowo et al. (2010) reported a low recovery efficiency of manure-derived N across Sub-Saharan Africa (median: 0.19 kg N kg^{-1}). As a result, despite the substantial quantities of manure applied to MCLS croplands and its significant contribution to total N (Figure 17), nutrient losses and low recovery efficiency likely influenced the observed yield outcomes (Figure 16). This is evident in the variable correlations between N applied and crop yields, ranging from weak to strong. In Burkina Faso, the correlations were: sorghum ($R^2 = 0.07$), green beans ($R^2 = 0.05$), and cowpea ($R^2 = 0.57$). In Ghana, the correlations were: 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 18). Furthermore, the absence of data on recommended N rates for onion and eggplant in Burkina Faso and tomato in Ghana (Figure 16c, d) indicates that the combined application of chemical fertilizer and manure (Figure 17) was insufficient to meet the specific N requirements of these vegetable crops.

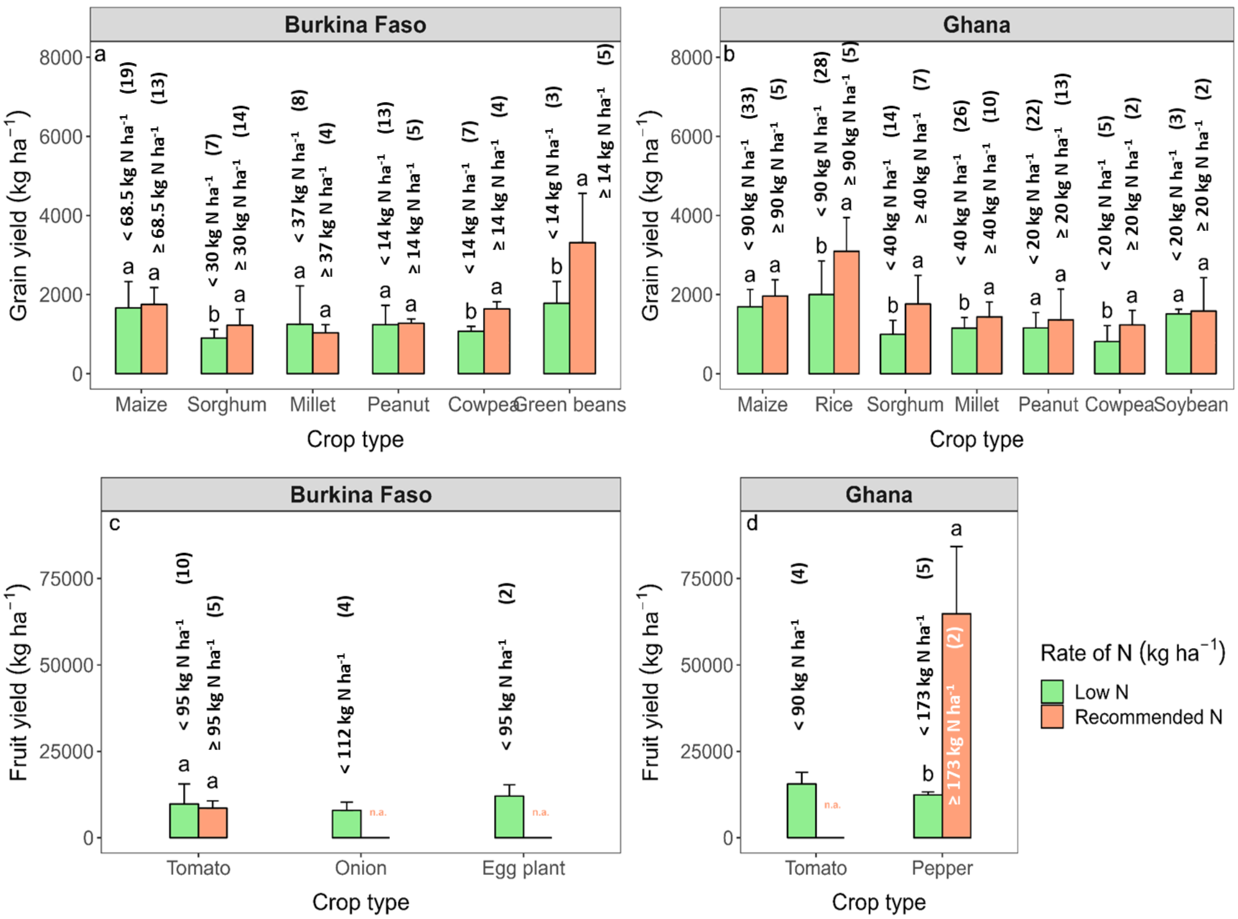

Figure 16. The effect of N rate (kg ha^{-1}) applied on grain (a – b) and fruit (c – d) yield in Burkina Faso and Ghana, respectively.

NB: 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 the N rate level for a crop type.

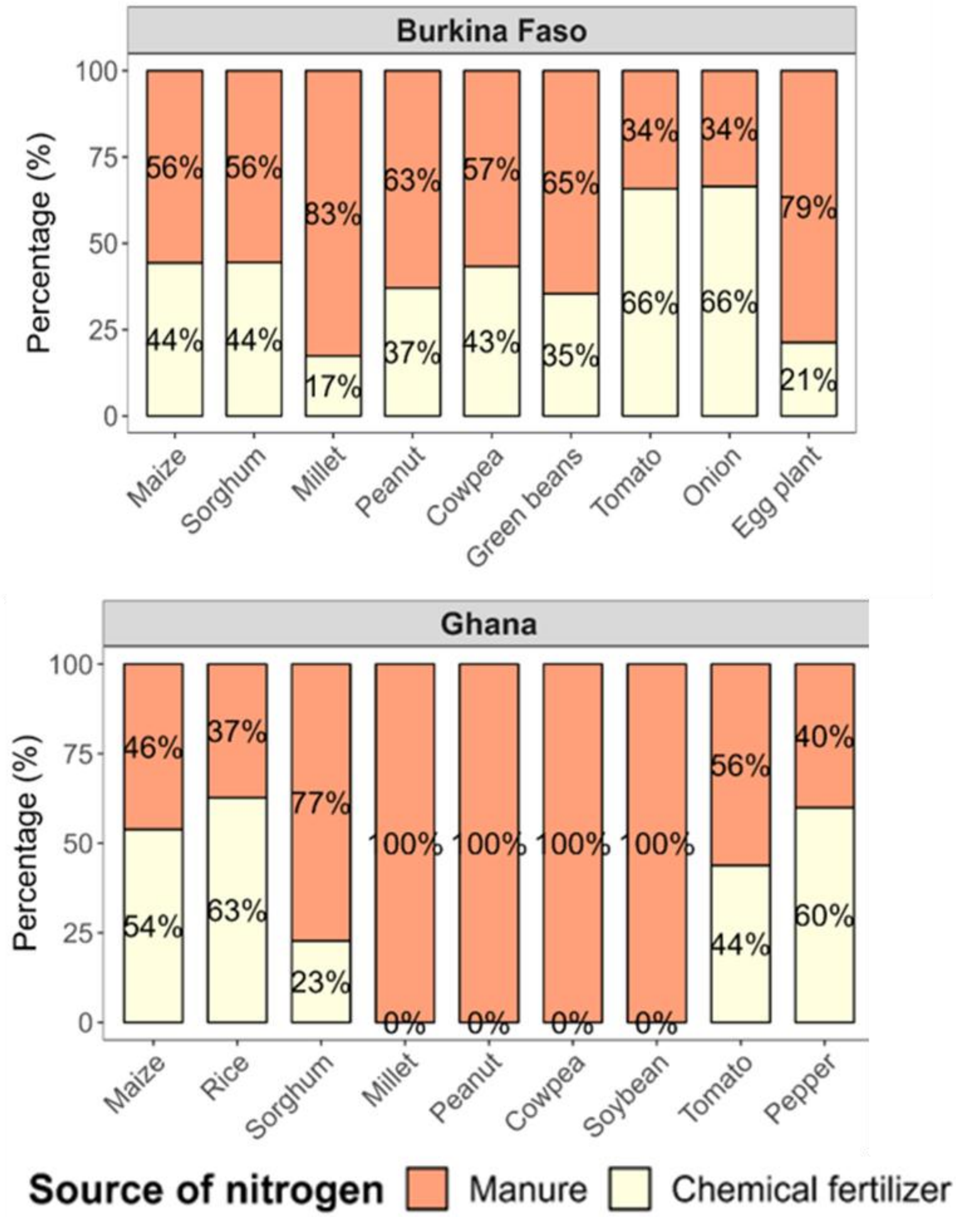

Figure 17. Contribution of manure and chemical fertilizer to the rate of N (Kg ha^{-1}) applied to crop type in MCLS farms.

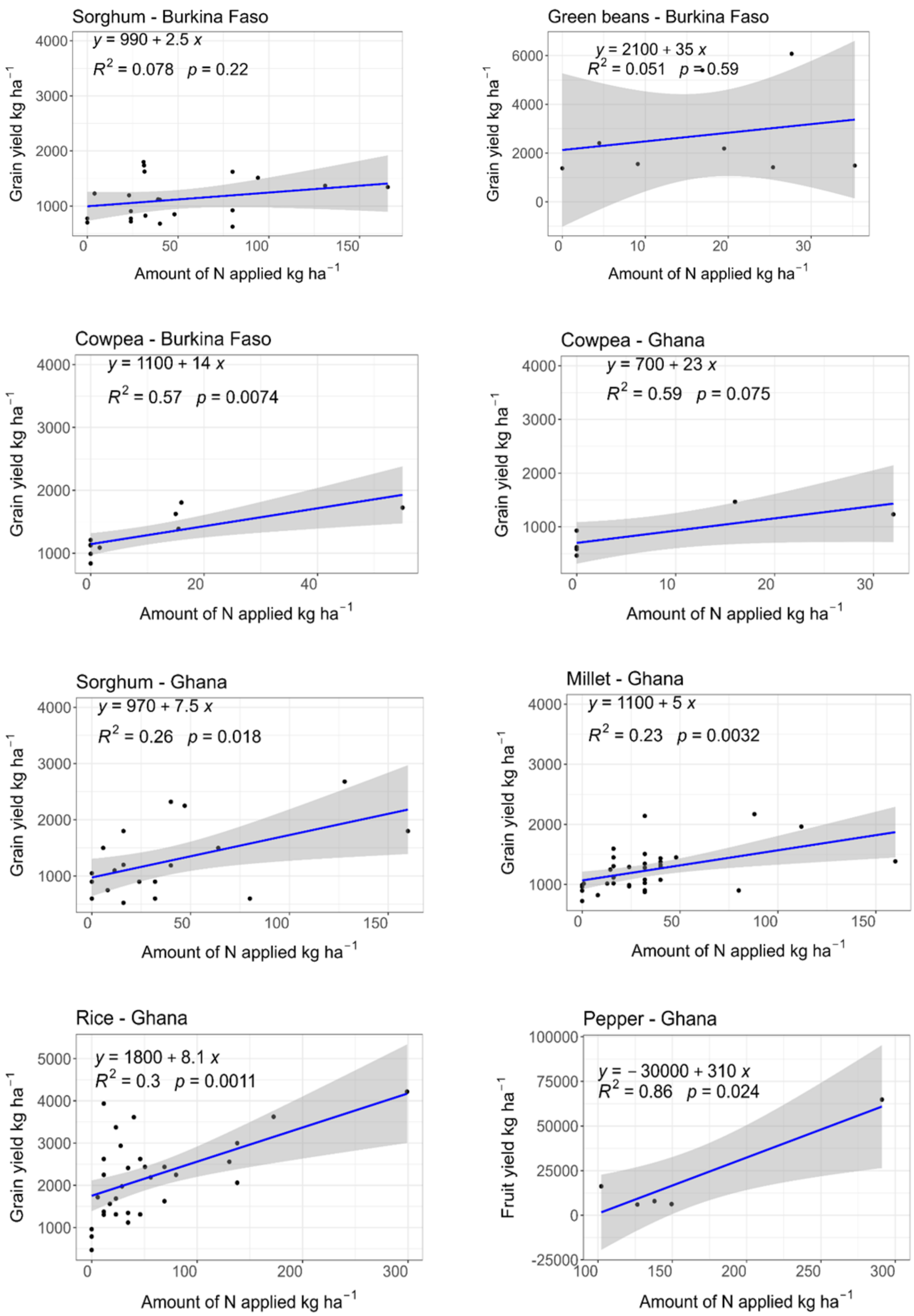

Figure 18. Variations between yields and the amount of N applied (kg N ha^{-1}) for grain and vegetable crops in Burkina Faso and Ghana (b). The solid blue line through the data points is a regression line.

4.3 Calibration and validation of SIMPLACE model for simulation of mixed crop-livestock systems in West Africa.

4.3.1 Evaluation of model performance

4.3.1.1 Maize grain yield

The comparison between observed and simulated maize grain yield for six districts; Bongo, Builsa North, Kassena Nankana (In Ghana) and Loumbila, Ziniaré, Zitenga (In Burkina Faso) are presented in Figures 19 and 23a. At the crop level, the model performance was reasonable for maize yield collectively across six districts, with RMSE value of 228.78 kg ha^{-1}, R^2 value of 0.01, and MR value of 3.06% (Figure 23a). Simulated maize yield at the district levels were found to be moderately overestimated at Bongo (MR = 11.86%, BQ = -184.44), Builsa North (MR = 11.69%, BQ = -180.87) and Loumbila (MR = 22.42%, BQ = -342.33). Conversely, the model underestimated at Kassena Nankana (MR = -16.18%, BQ = 315.59) and Zitenga (MR = -11.19, BQ = 174.62). However, the best model performance was observed at Ziniare (MR = -0.26%, BQ = 4.96) (Appendix 9). Observed data used for this analysis, consisted of district-aggregated records from typical mixed crop–livestock farming systems which consist of a wide range of maize cultivars and yield potentials. This implies under no limiting factors (water, nutrients) and no reducing factors (weeds, pests and disease), the duration of the vegetative and reproductive period becomes the critical factor for capturing the dynamics of simulated maize yield. Previous studies that employed SIMPLACE similarly reported on the contribution of maize cultivar or heterogeneity (even under the same conditions) to yield uncertainties (Kamali et al., 2022; Nguyen et al., 2022).

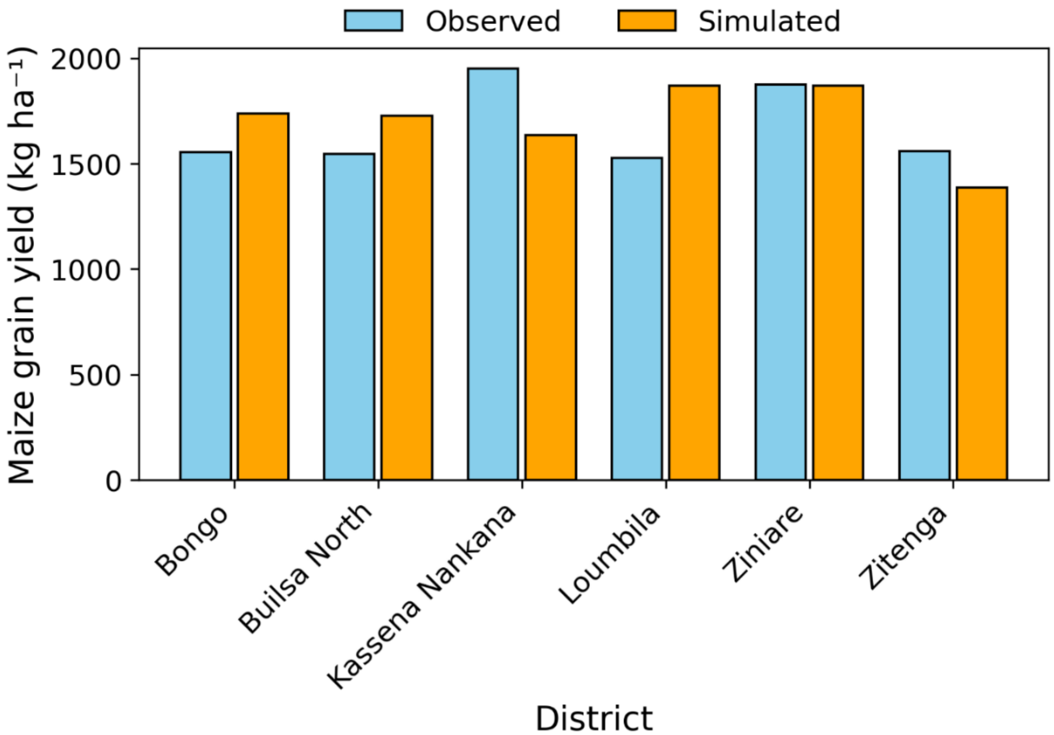

Figure 19. Model calibration and validation for maize grain yield (from 2000 – 2024) at the district level in Ghana (Bongo, Builsa North, Kassena Nanakana) and Burkina Faso (Loumbila, Ziniare, Zitenga).

4.3.1.2 Millet grain yield

Simulated millet yield when compared with observed yields resulted in a RMSE value of 139.89 kg ha^{-1}, R^2 value of 0.96, and MR value of -12.08% (Figure 23b). The model's predictions for the millet yield were consistently underestimated at all six districts; Bongo (MR = -0.12, BQ = 155.55), Builsa North (MR = -0.20, BQ = 264.18), Kassena Nankana (MR = -0.07, BQ = 76.50), Loumbila (MR = -0.17, BQ = 77.49), Ziniaré (MR = -0.10, BQ = 88.31), and Zitenga (MR = -0.04, BQ = 61.33) (Figure 20; Appendix 9). This could possibly be due to the model's inability to account for field-level heterogeneity in management practices. For instance, management practices such as planting date are not homogeneous for farmers. Therefore, considering a planting window as representative of an entire district could reduce the model accuracy in terms of yield simulation. Srivastava et al. (2016) indicated that decisions about sowing dates are more complex than those assumed in existing crop models. In line with this, model simulations have already shown yield reductions depending on planting dates in semi-arid Eastern Africa (Silungwe et al., 2019). Therefore, refining the model inputs to incorporate field-specific planting dates could improve our simulations to outcomes which are in agreement with observed field data. Nonetheless, the overall model performance was satisfactorily with the relatively low RMSE.

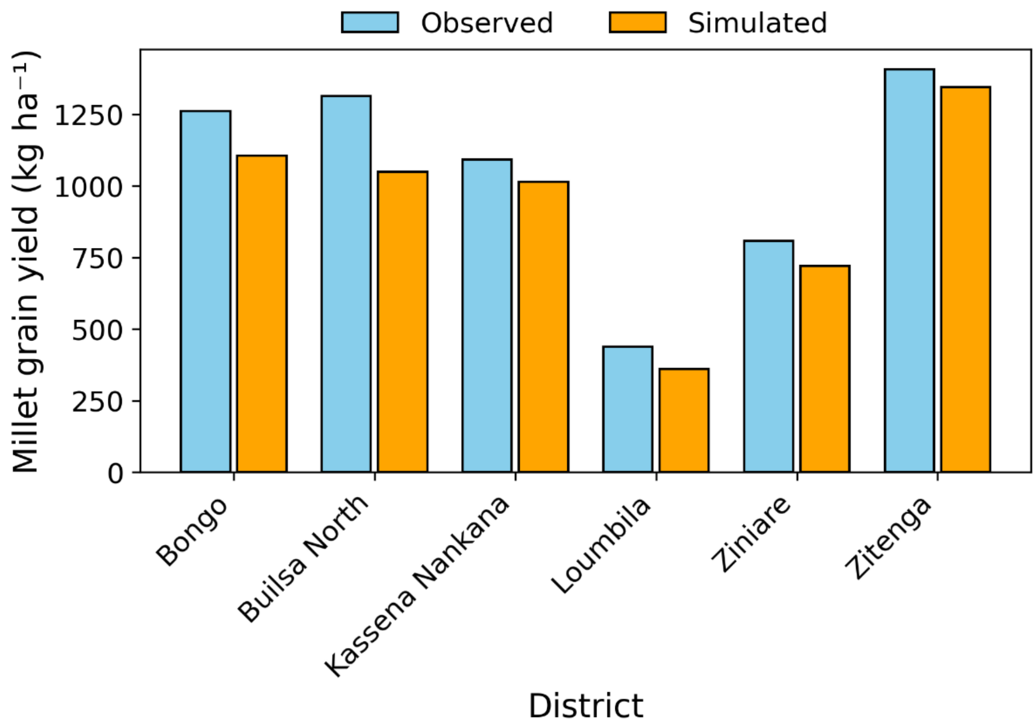

Figure 20. Model calibration and validation for millet grain yield (from 2000 – 2024) at the district level in Ghana (Bongo, Builsa North, Kassena Nanakana) and Burkina Faso (Loumbila, Ziniare, Zitenga).

4.3.1.3 Sorghum grain yield

The comparison between observed and simulated sorghum grain yield for six districts; Bongo, Builsa North, Kassena Nankana (In Ghana) and Loumbila, Ziniaré, Zitenga (In Burkina Faso) are presented in Figures 21 and 23c. The model performance was satisfactorily with an RMSE value of 263.22 kg ha^{-1}, R^2 value of 0.34, while the MR, on average produced ~18 % deviation between simulated and the observed yields (Figure 23c). The prediction of sorghum yield when applying the calibrated model for the different districts is illustrated in Figure 21. The model over estimated sorghum yields at Bongo (MR = 0.25. BQ = -313.82), Builsa North (MR = 0.08, BQ = -132.99), Kassena Nankana (MR = 0.27, BQ = -334.11), Loumbila (MR = 0.06, BQ = -82.53), and Ziniaré (MR = 0.46, BQ = -420.55) (Appendix 9). However, at Zitenga the model was slightly underestimated by an MR value of -0.05 and a BQ value of 64.96 (Figure 21; Appendix 9). It was evident that the model adequately represents overall yield patterns across districts, maintaining the relative order between higher- and lower-yielding areas in the simulated data. This suggests that the SIMPLACE model can effectively simulate sorghum yields at the field scale. In the Sudan Savannah regions of West Africa, most sorghum farmers either do not apply fertilizer or cultivate sorghum on less fertile soils (Adam et al., 2020). Such uniformity in management practices may reduce yield uncertainties, thereby minimizing discrepancies between simulated and observed data. These findings are also consistent with the results of Akinseye et al. (2017), who evaluated crop model enhancements by comparing sorghum simulation outputs in West Africa.

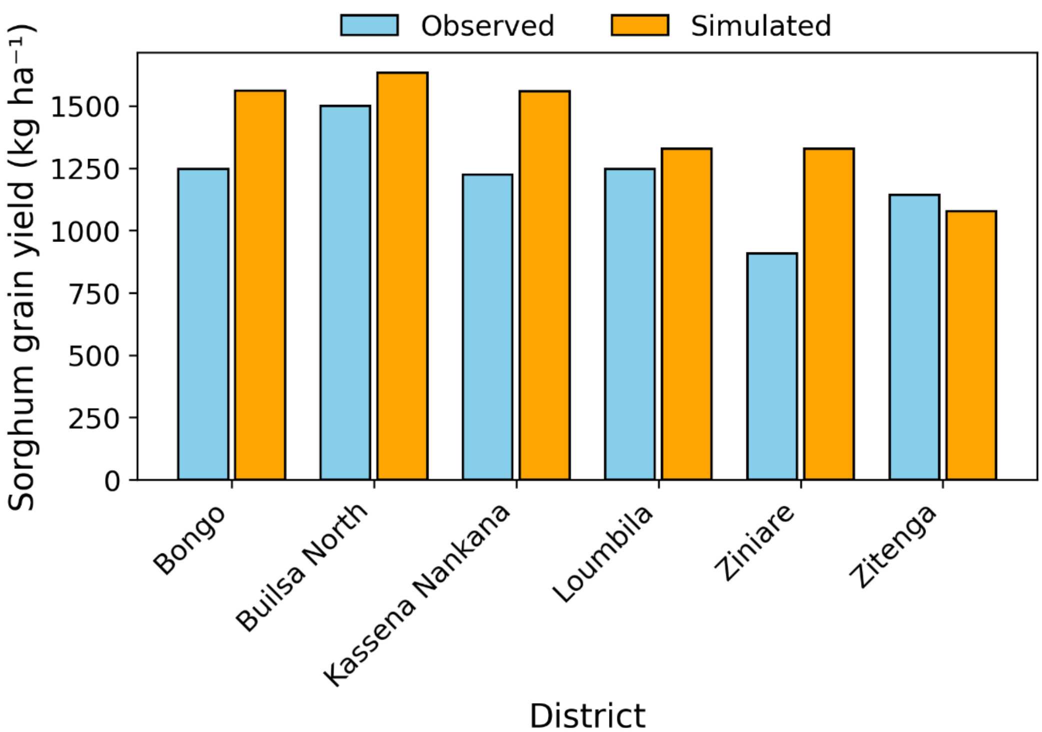

Figure 21. Model calibration and validation for sorghum grain yield (from 2000 – 2024) at the district level in Ghana (Bongo, Builsa North, Kassena Nanakana) and Burkina Faso (Loumbila, Ziniare, Zitenga).

4.3.1.4 Peanut grain yield

The comparison between observed and simulated peanut grain yields for six districts; Bongo, Builsa North, and Kassena Nankana (in Ghana) and Loumbila, Ziniaré, and Zitenga (in Burkina Faso) is illustrated in Figures 22 and 23d. The model demonstrated satisfactory performance for yield, with an RMSE of 276.60 kg ha^{-1}, and an R^2 value of 0.21. Additionally, the mean residual (MR) revealed an average deviation of approximately -13.36% between simulated and observed yields (Figure 23d). The model's predictions for peanut yield at the district levels were found to be slightly underestimated at Bongo (MR = -0.19%, BQ = 290.82), Loumbila (MR = -0.06%, BQ = 73.33), Ziniare (MR = -0.17, BQ = 220.93), and Zitenga (MR = -0.42, BQ = 562.52). Conversely, the model slightly overestimated at Kassena Nankana (MR = 0.05%, BQ = -61.88). However, the best model performance was observed at Builsa North (MR = 0.00%, BQ = -4.10) (Appendix 9). The relatively low mean residual (MR) values across all six districts indicate minimal discrepancies between simulated and observed peanut yields. Similarly, the RMSE and MR values at the crop level reflect strong agreement between simulated and observed data. This concordance likely stems from the high-quality calibration data, as the yield range used for calibration (1000–1400 kg ha^{-1}) closely approximates the field-reported yield of approximately 1100 kg ha^{-1} in West Africa (Adjei-Nsiah et al., 2018).

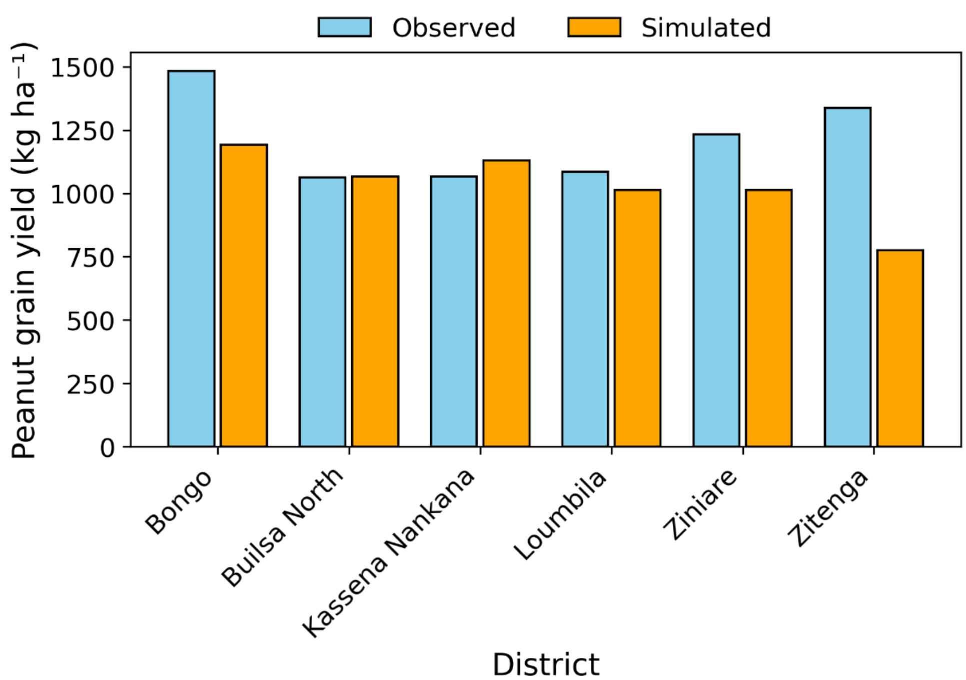

Figure 22. Model calibration and validation for sorghum grain yield (from 2000 – 2024) at the district level in Ghana (Bongo, Builsa North, Kassena Nanakana) and Burkina Faso (Loumbila, Ziniare, Zitenga)

Overall, the best model performance was observed for millet, with the lowest RMSE, although all crops showed reasonable results with RMSE < 278 kg ha^{-1} and MR < 19 %. No particular trends were observed with regards to model performance by location (Figure 23).

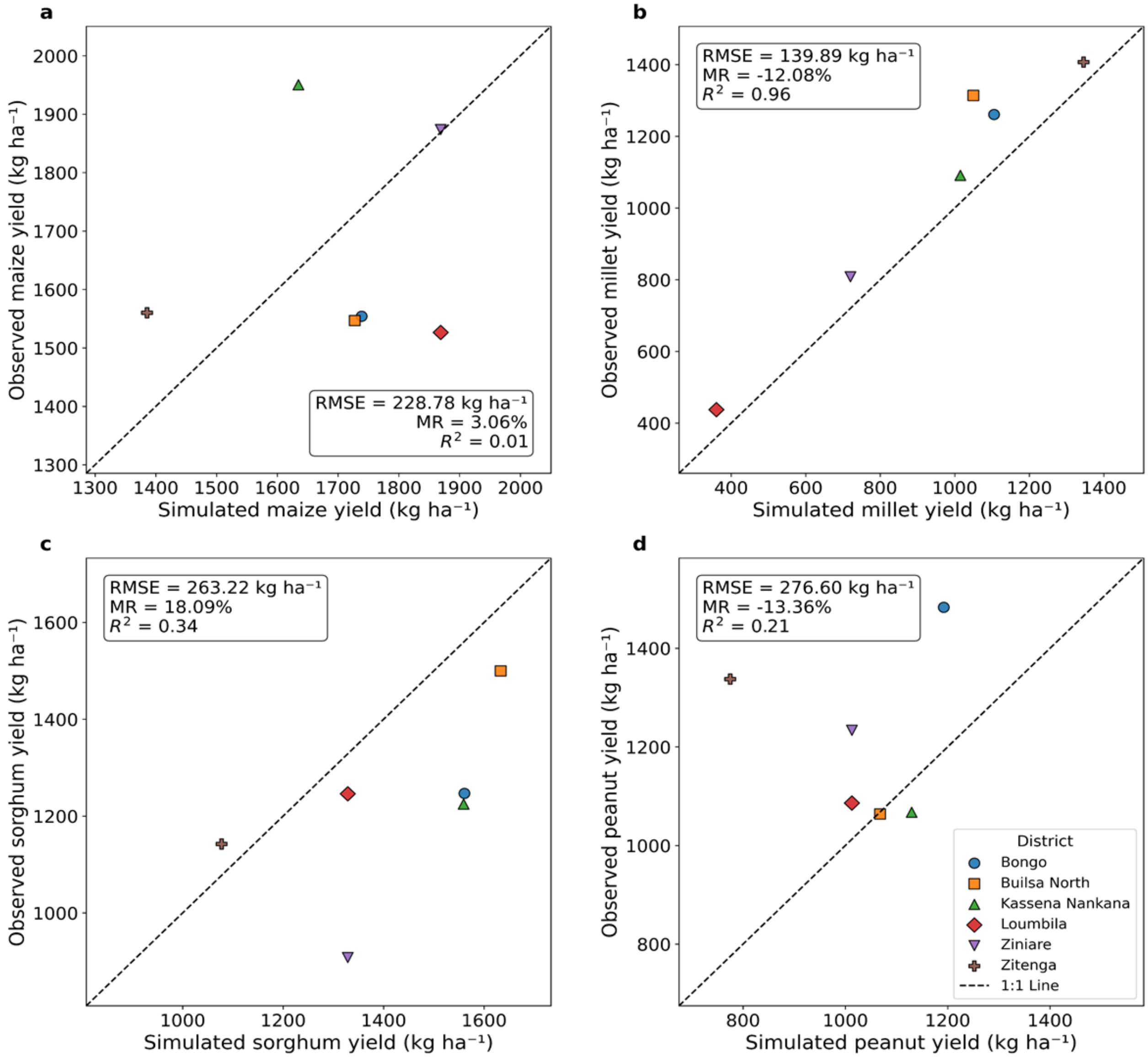

Figure 23. 1:1 Comparison of simulated and observed (a) maize, (b) millet, (c) sorghum, and (d) peanut grain yields across six districts.

4.3.1.4 Livestock population estimation

For livestock population, the comparison between observed and simulated numbers for six districts; Bongo, Builsa North, Kassena Nankana (In Ghana) and Loumbila, Ziniaré, Zitenga (In Burkina Faso) are presented in Figures 24a and b. At the livestock level, the model prediction looks reliable for capturing livestock numbers collectively across six districts with an RMSE value of 29.90, R^2 value of 0.62, and an MR value of 27.59% (Figure 24b). Our result is consistent with Srivastava et al. (2025) who observed a model prediction for the livestock population in the

Sudanian region of West Africa with an MR value of 24.5%. On the other hand, the model's prediction for livestock numbers at the district level was found to be slightly overestimated at Bongo (MR = 0.38, BQ = -40.03), Builsa North (MR = 0.69, BQ = -48.70) and Kassena Nankana (MR = 0.31, BQ = -35.24). In contrast, the model's best performance was at Loumbila (MR = 0.05, BQ = -4.70), Ziniare (MR = 0.05, BQ = -4.70) and Zitenga (MR = 0.15, BQ = -10.22) (Appendix 10). In the present study, livestock population dynamics were simulated by tracking animal numbers and their transitions across age groups, primarily regulated by birth rates, mortality, offtake, and intake rates. The model's performance at the district level suggests its capacity to effectively represent these transition processes. Furthermore, the livestock population included a mix of species (cattle, sheep, and goats) each with distinct reproductive and mortality characteristics, which can contribute to variability in population estimates. Hence, the model's ability to reflect these interspecies differences suggests that irrespective of the livestock type, with the SIMPLACE integrated framework model one can already obtain acceptable livestock population predictions.

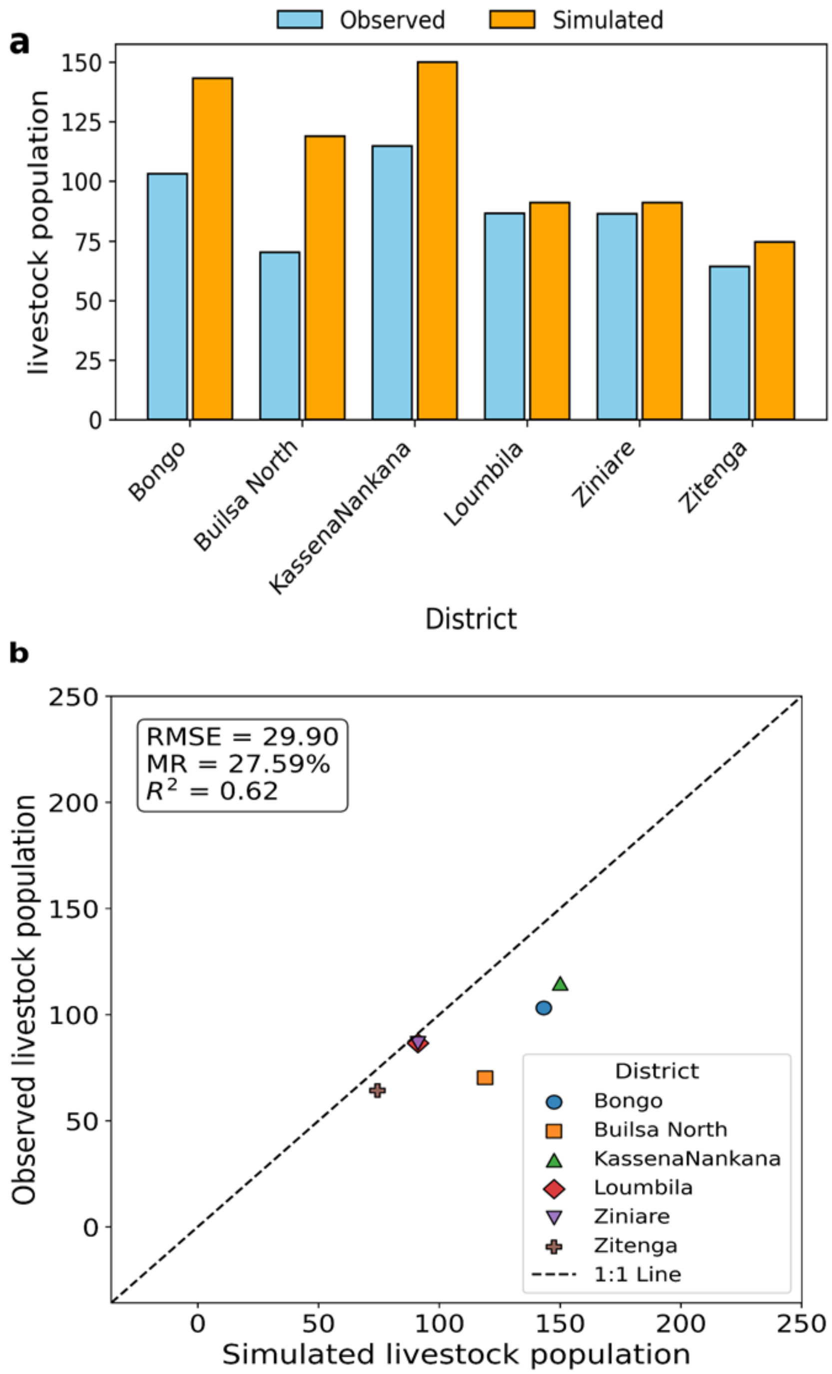

Figure 24. (a): Model calibration and validation for livestock number (from 2000 – 2024) and (b): 1:1 Comparison of simulated and observed livestock numbers at the district level in Ghana (Bongo, Builsa North, Kassena Nanakana) and Burkina Faso (Loumbila, Ziniare, Zitenga)

4.4 Simulating climate change impacts on MCLS for mid-century

4.4.1 Projected future climate change

After calibrating and validating to assess the potential of SIMPLACE, in simulating the output of typical crop-livestock farms, the validated model was applied to estimate the effect of climate change on MCLS at farm scale in the Sub-humid savannah of West Africa.

4.4.1.1 Rainfall under historical and future scenario

The Study districts in Burkina Faso (Loumbila, Ziniaré, Zitenga) and Ghana (Kassena Nankana, Builsa North, Bongo) have only one rainy season from May to mid-October. These rainy seasons are most important because they influence seasonal and annual rainfall patterns during the past, present and projected (Arfasa et al., 2024). In the historical era from 2000 – 2024, the average cumulative rainfall was between 400 mm and 667 mm for the districts in Burkina Faso (Loumbila, Ziniaré, Zitenga) and in Ghana (Kassena Nankana, Builsa North, Bongo), respectively (Figure 25). Looking to the future, from 2025 – 2050, the projections indicate a decrease in average cumulative rainfall, with values ranging from 517 mm to 366 mm for the districts in both countries, respectively (Figure 25). Moreover, compared to the historical data, the areas in Ghana and Burkina Faso are anticipated to see a decrease in rainfall by 14.2 – 16.6% and 5.0 – 12.5%, respectively (Figure 25). Comparable findings have been reported for the Sudan Savannah zone of Ghana by Arfasa et al. (2024), where mean annual precipitation under the SSP 4.5 emission scenario is projected to decline by approximately 12.3% to 13.1%. Similarly, research conducted in the Dano region of Burkina Faso indicated reductions in mean annual rainfall by 25.2% and 25.6% under the RCP 4.5 and RCP 8.5 scenarios, respectively (Okafor et al., 2021). These projected declines in precipitation are anticipated to intensify drought conditions across the Sudan Savannah of West Africa in the coming decades (Ayanlade et al., 2022). Additionally, the spatial distribution of future rainfall suggests a latitudinal shift, with precipitation zones moving from districts in Burkina Faso toward those in northern Ghana. As a result, a southward displacement of isohyets by 150 to 200 km has been observed within the Sudan Savannah region (OSS, 2019).

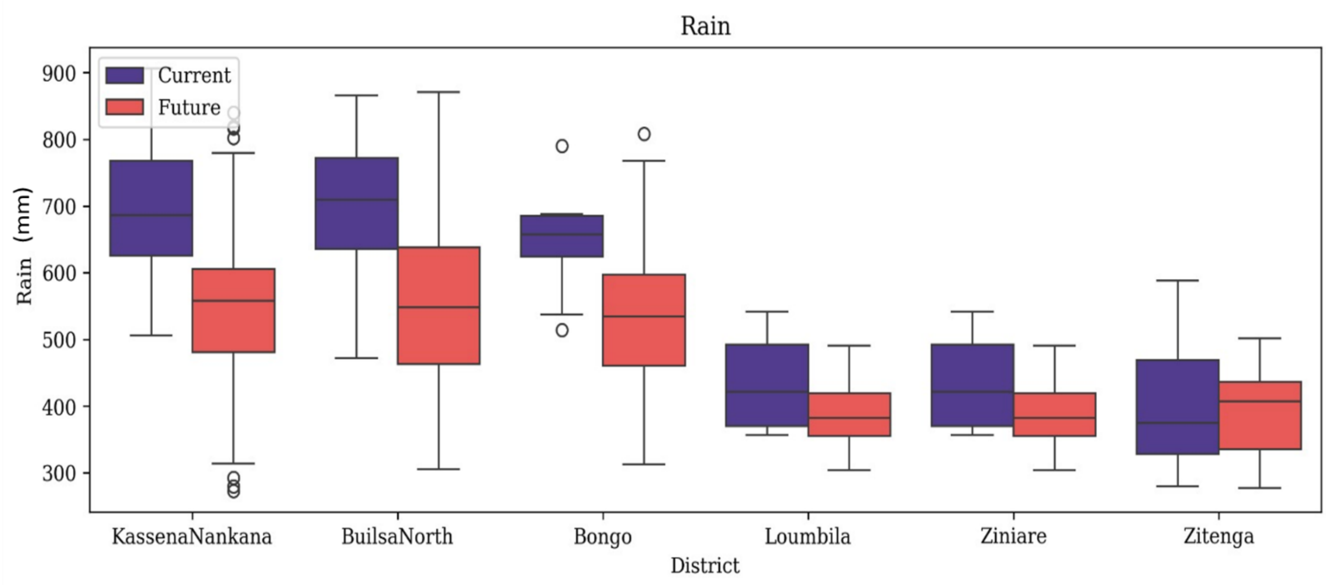

Figure 25. Current (2000 – 2024) and future (2025 – 2050) mean annual rainfall in Kassena Nankana, Builsa North, Bongo (Ghana) and Loumbila, Ziniare, Zitenga (Burkina Faso) for the model *GFDL-ESM4*.

4.4.1.2 Minimum and maximum temperature under historical and future scenario

In this study, projections for the period 2025–2050 indicate an increase in minimum temperature (Tmin) across the Ghanaian districts by approximately 0.7 ℃ to 1.0 ℃ (3.2% - 4.3%), and by 1.5 ℃ to 1.7 ℃ (6.6% - 7.4%) in the districts located in Burkina Faso, relative to the historical baseline (Figure 26). Notably, the presence of outliers in the projected Tmin values for Bongo, Loumbila, and Ziniaré suggests considerable variability, which may introduce uncertainty and potentially moderate the projected temperature increases in these areas (Figure 26). Likewise, projections indicate an increase in maximum temperature (Tmax) for the period 2025–2050, with estimated rises ranging from 0.2 °C to 0.5 °C (0.58%–1.44%) in the Ghanaian districts and from 0.4 °C to 0.9 °C (1.12%–2.54%) in the districts of Burkina Faso, relative to historical observations (Figure 27). The findings of this study suggest that, by the middle of the century, the study districts are predicted to experience a rise in temperature, potentially shifting the region toward more arid conditions (Sawadogo et al., 2024). This warming trend is also expected to increase the frequency of hot days annually (Trisos et al., 2022). The projected temperature rise in our study aligns with the estimates provided by Trisos et al. (2022), who reported that under global warming scenarios of 1.5°C, 2.0°C, and 3.0°C, mean annual temperatures in West Africa are expected to increase by approximately 0.6°C, 1.1°C, and 2.1°C, respectively. Such temperature increases are anticipated to negatively affect agricultural systems, potentially leading to reduced crop yields or crop failure (Sawadogo et al., 2024), while also exerting pressure on livestock productivity and adaptability across different species and breeds (Zougmoré et al., 2016).

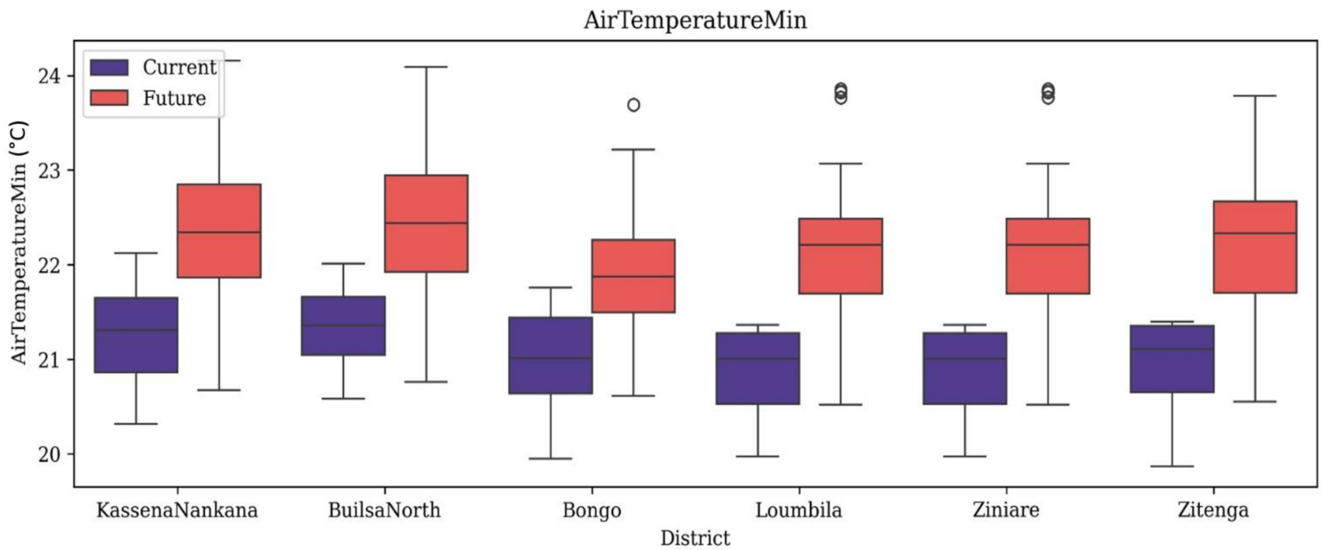

Figure 26. Current (2000 – 2024) and future (2025 – 2050) mean annual minimum air temperature (°C) in Kassena Nankana, Builsa North, Bongo (Ghana) and Loumbila, Ziniaré, Zitenga (Burkina Faso) for the model *GFDL-ESM4*.

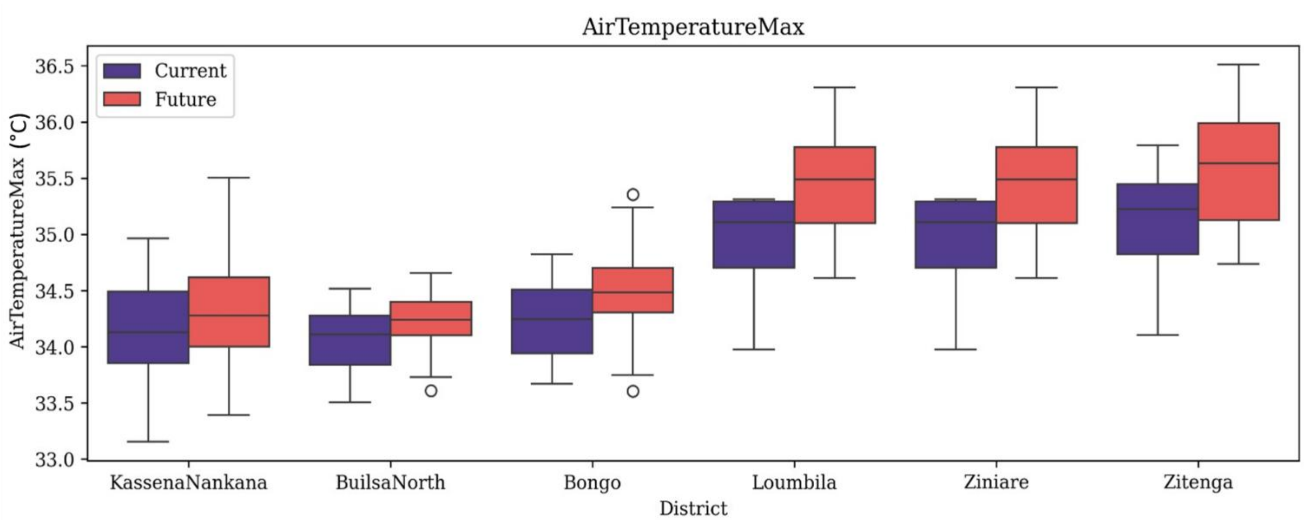

Figure 27. Current (2000 – 2024) and future (2025 – 2050) mean annual maximum air temperature (°C) in Kassena Nankana, Builsa North, Bongo (Ghana) and Loumbila, Ziniaré, Zitenga (Burkina Faso) for the model *GFDL-ESM4*.

4.4.2 Crop yield under future climate scenarios

4.4.2.1 Maize grain yield

Simulated maize grain yield under baseline and future climate scenarios across six districts; Bongo, Kassena Nankana, Builsa North (Ghana) and Loumbila, Ziniaré, Zitenga (Burkina Faso) are shown in Figure 28a. When comparing the future scenario to the baseline, our results indicated a consistent decline in maize grain yield across all districts with Burkina Faso being the most affected (Figure 28a). When compared to the historical yield data, the districts in Ghana and Burkina Faso are anticipated to see a decline in grain yield by -15.89% to -22.03% and -30.39 to 34.74%, respectively (Figure 29a). Previous studies confirm that climate change is having a predominantly negative impact on maize grain yield in Africa (Shi and Tao, 2014). In using three GCM's (ECHAM6, MIROC5, NorESMI), Faye et al. (2018) found maize grain yield changes of -5% in the West African Sudan savannah. Nafi et al. (2021) reported a projected grain yield change of -11% for maize cultivated on poor soil with low water retention. More recently, Srivastava et al. (2025) identified substantial yield reductions of up to 88% under multiple GCM simulations (CCLM-MPI-ESM, WRF-HADGEM2, and WRF-MPI-ESM) in the same agro-ecological region.

4.4.2.2 Millet grain yield

Millet exhibited a similar declining trend in grain yield as observed for maize under future climate scenarios (Figure 28b). Relative to the historical baseline, projections indicate that districts in Ghana may experience reductions in millet grain yield ranging from -22.51% to -33.54%, however, the largest reduction of -54.72% to -57.81% could occur in Burkina Faso (Figure 29b). These findings are consistent with prior regional studies, which have reported diverse changes in millet yield across the Sudanian and Sahelian zones of West Africa, including changes of 0% to 41% (Sultan et al., 2013), -5% to -10% (Maccarthy et al., 2021), -11% (P. Singh et al., 2017), and even -78.2% (Srivastava et al., 2025). The observed variation across districts in our study supports the variations reported in the previous studies. Although it is difficult to attribute these variations to a single factor, differences in cultivars commonly used by crop-livestock farmers may partly explain the disparities. Several simulation studies conducted in the Sudanian and Sahelian savannah zones of West Africa have demonstrated that climate change impacts are not uniform across all millet cultivars. Losses tend to be greater in high-yielding modern cultivars characterized by short growth cycles (Sultan et al., 2013). For instance, Sultan et al. (2023) reported yield reductions of 47% and

44% for short-cycle and long-cycle millet varieties, respectively, under the RCP8.5 emission scenario.

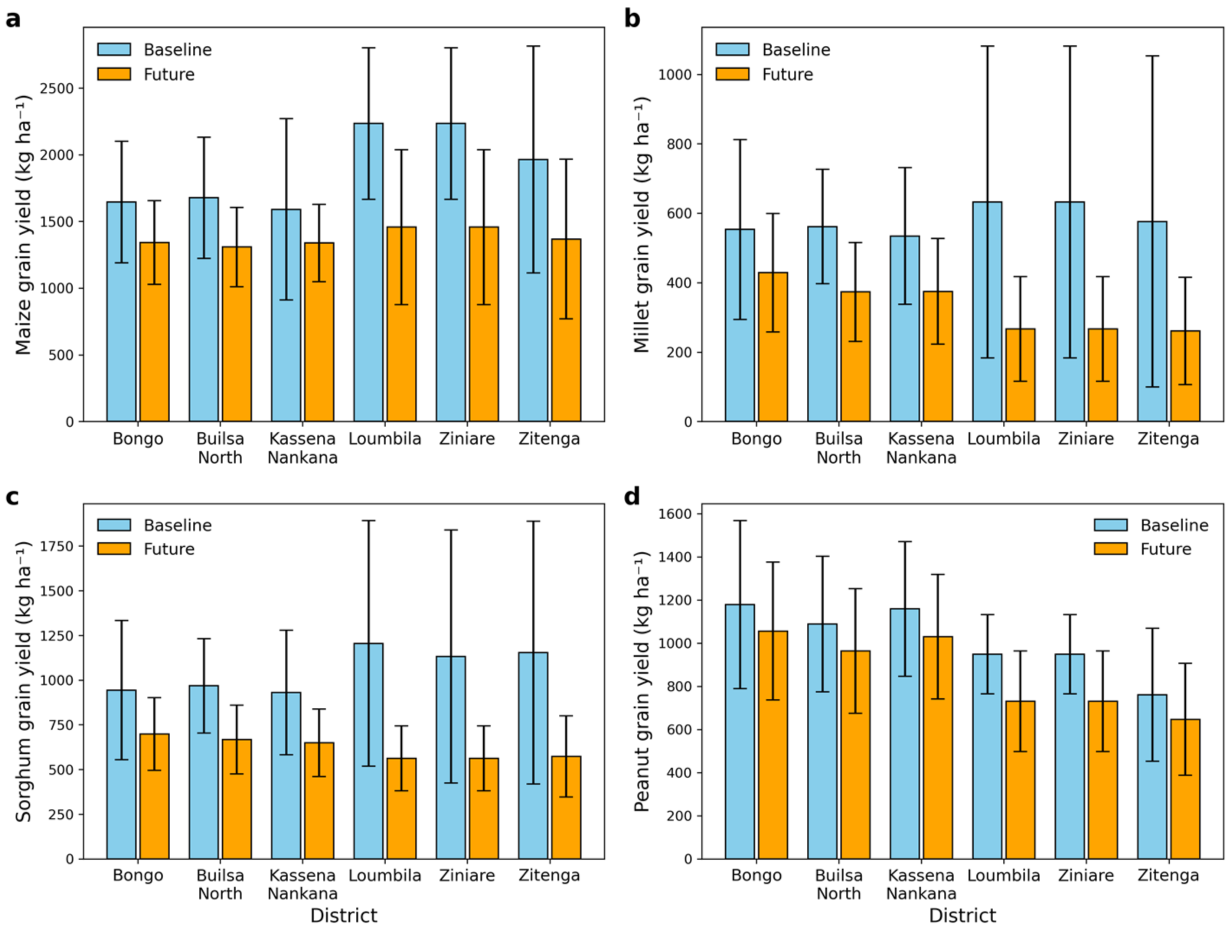

Figure 28. Grain yield (a) Maize, (b) Millet, (c) Sorghum and (d) Peanut in future scenarios (2025-2050) compared to baseline (2000-2024) in Kassena Nankana, Builsa North, Bongo (Ghana) and Loumbila, Ziniare, Zitenga (Burkina Faso). Error bars represent the standard deviation.

4.4.2.3 Sorghum grain yield

Model simulations projected a consistent decline in sorghum grain yield across all study districts; Bongo, Kassena Nankana, and Builsa North in Ghana, as well as Loumbila, Ziniaré, and Zitenga in Burkina Faso, when compared to the baseline period (Figure 28c). Specifically, grain yield reductions are estimated to range from −26.03% to −31.07% in the Ghanaian districts, and from −50.29% to −53.38% in those of Burkina Faso (Figure 29c). The magnitude of the decline is notably more pronounced in the districts within Burkina Faso, suggesting a higher level of vulnerability to projected climatic changes. However, the relatively large standard deviations observed for both baseline and future yields indicate a degree of uncertainty in the model outputs (Figure 28c). Nonetheless, these findings align with earlier work by Sultan et al. (2014), which showed that climate change leads to yield declines in sorghum across West Africa, including regions in the central Sahel where precipitation may be increasing. Furthermore, the observed variability in projected yields may indicate an increased risk of crop failure under warmer conditions. In this study, future scenarios showed relatively higher maximum temperatures in the Burkina Faso districts (Figure 27), which could further exacerbate the negative impact on yield. Previous studies on C_4 crops such as maize (Schlenker and Lobell, 2010), millet, and sorghum (Sultan et al., 2013) have consistently identified elevated temperatures as a primary driver of yield reductions under climate change scenarios. Therefore, identifying the most vulnerable regions and developing crop varieties with enhanced resilience should be a priority for designing effective adaptation strategies.

4.4.3.4 Peanut grain yield

Figure 28d illustrates the simulated peanut grain yields under baseline and future climate conditions across six districts; Bongo, Kassena Nankana, and Builsa North in Ghana, along with Loumbila, Ziniaré, and Zitenga in Burkina Faso. A comparison of future projections against the baseline indicates a consistent decline in peanut yields across all locations (Figure 28d). Specifically, yield reductions are estimated to range from −10.47% to −11.46% in the Ghanaian districts and −15% to −23% in those of Burkina Faso (Figure 29d). Notably, the magnitude of projected yield decline is greater in the Burkina Faso districts compared to those in Ghana. The extent of yield reduction for peanuts is smaller relative to the declines observed for maize, millet, and sorghum in this study (Figures 29a, 29b and 29c). This observation contrasts with findings by Van Duivenbooden et al. (2002), who argued that groundnut is more vulnerable to climate variability than millet, primarily due to its shallow root system and reliance on the more heat-sensitive C3 photosynthetic pathway, unlike the more heat-resilient C4 pathway used by millet and maize (Van Duivenbooden et al., 2002). Similarly, Faye et al. (2018a) reported increases in peanut yields under rain-fed conditions, projecting gains of 11% and 19% under RCP 4.5 and RCP 8.5 scenarios, respectively. Nonetheless, the results of the present study are in line with those reported by Sarr and Camara (2018), who also documented reductions in peanut grain yield using simulations conducted with the DSSAT model.

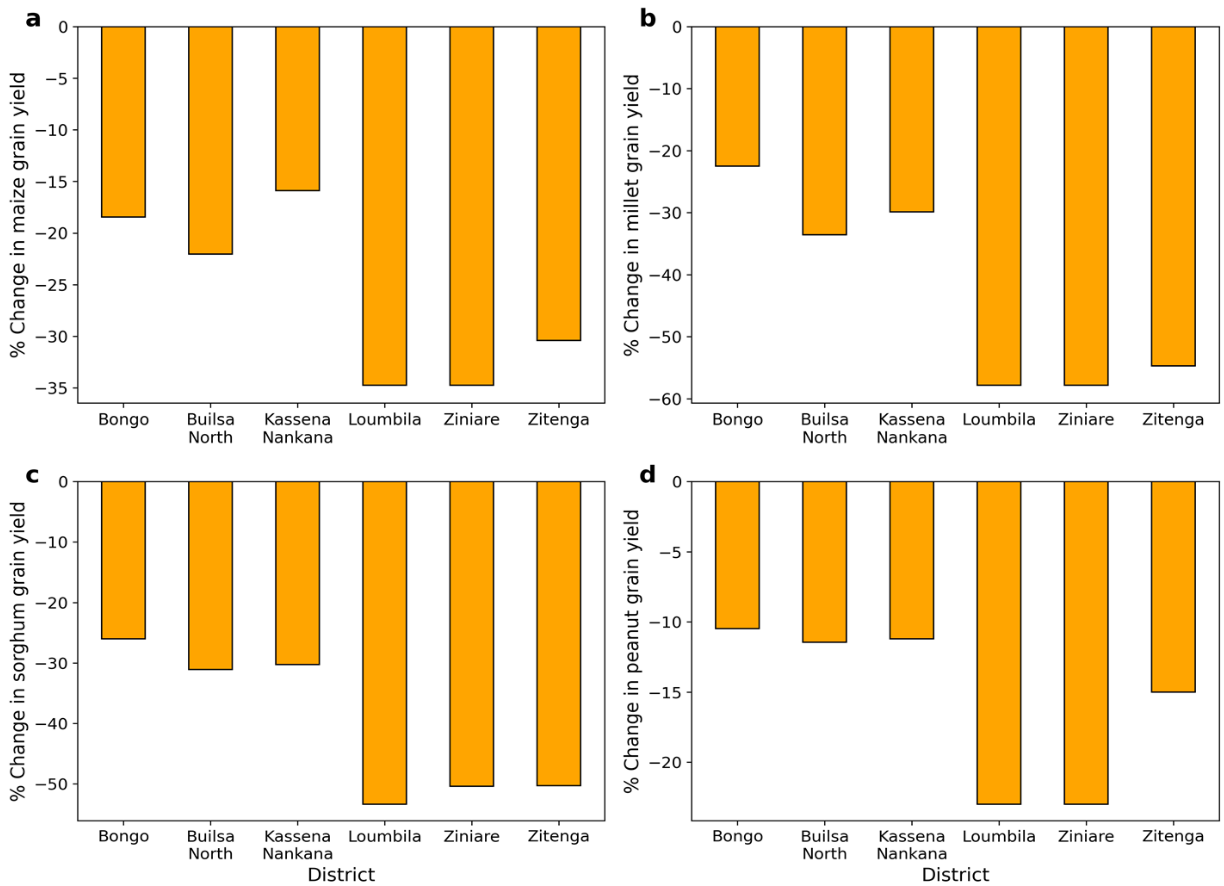

Figure 29. Percentage change in grain yield (a) Maize, (b) Millet, (c) sorghum, and (d) peanut in future scenarios (2025-2050) for Kassena Nankana, Builsa North, Bongo (Ghana) and Loumbila, Ziniaré, Zitenga (Burkina Faso)

4.4.3 Livestock number under future climate scenarios

Model projections indicate a consistent increase in livestock numbers across all study districts, including Bongo, Kassena Nankana, and Builsa North in Ghana, as well as Loumbila, Ziniaré, and Zitenga in Burkina Faso (Figure 30a). Specifically, livestock populations are projected to rise by approximately 181.73% to 181.75% in Ghanaian districts and by 181.65% to 181.67% in those located in Burkina Faso (Figure 30b). Notably, the absolute increases are more pronounced in the Ghanaian districts. These projected trends may have significant implications for mixed crop-livestock systems (MCLS) within the study regions, given the important role of livestock in enhancing system productivity. Livestock contributes to food, draught power, manure production, and socio-economic support at the farm level (Herrero et al., 2010; Peden et al., 2007). However, a simultaneous rise in livestock numbers (Figure 30a and b) and a projected decline in forage availability due to climate change (Godde et al., 2020) may present substantial challenges. Previous research indicates that grass biomass could decline by as much as 57% across the Sudanian and Sahelian zones of West Africa under future climate conditions (Srivastava et al., 2025). On a broader scale, global herbaceous biomass is projected to decrease by 4.7% by 2050 under RCP 8.5 (Godde et al., 2020). These dynamics suggest that the projected rise in livestock populations, in tandem with decreasing forage resources, could exacerbate grazing pressure, necessitating robust planning and sustainable pasture management strategies in the study regions.

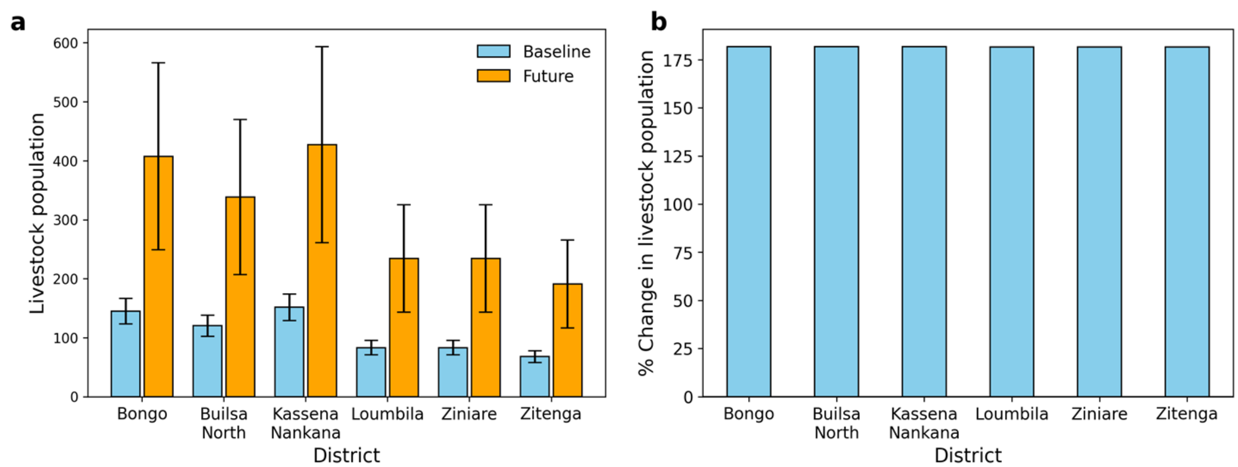

Figure 30. (a) Livestock number in future scenarios (2025-2050) compared to baseline (2000-2024) and (b) percentage change in livestock number in future scenarios (2025-2050) for Kassena Nankana, Builsa North, Bongo (Ghana) and Loumbila, Ziniaré, Zitenga (Burkina Faso).

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The assessment of the productivity of mixed crop-livestock farms in the Sudan savannah of West Africa through survey studies, model application, and climate scenario analysis was relatively successful in determining soil GHG emissions in MCLS, yield response to fertilizer practices, and projected grain yield of farmers under future climate scenarios.

The objective of the meta-analysis was to determine the response patterns of nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) emissions in MCLS across diverse environments and management scenarios. The study revealed that, drainage classes, stocking density, climate, soil texture, amount and type of nitrogen (N) fertilizers emerged as the primary contributors to both N_2O and CH_4 emissions. However, differences in CO_2 emissions within categories of stocking density, climate, crop type, livestock type, tillage, N fertilizer amount and type were not significantly affected by MCLS. The primary moderating variables of GHGs emissions (N_2O, CH_4, CO_2) from MCLS were, in descending order of importance: drainage class, stocking density, climate, amount of N fertilizer, fertilizer type, soil texture, crop type, tillage, livestock type, and MCLS type.

Source of fertilizer, method of fertilizer application, timing of fertilizer application and the amount of nitrogen (N) are all fertilizer practices that influenced crop yield and should be considered as we aim to close yield gaps. In this study, no substantial reduction in grain and vegetable yields was observed when combining manure and chemical fertilizer to supply the crop nutrient demands. Applying fertilizer in furrows showed that subsurface application may be advantageous for improving yields even under adverse weather conditions such as drought or excessive rainfall. High variability between crop types and countries characterized yield responses to the timing of chemical fertilizer and manure applications. 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.

The study on simulation modelling provides insights into the SIMPACE model's predictions across various MCLS farms and locations. The results suggest that at the district the model exhibited a slight and moderate overestimation of maize and sorghum grain yields, respectively, while it underestimated the yields of millet and peanut. Although the overall RMSE and MR values were within acceptable limits, variability was observed at the district level across crop types. For instance, the model underestimated maize yields in Kassena Nankana and Zitenga, as well as sorghum yields in Zitenga, whereas an overestimation of peanut yield was noted in Kassena Nankana. In terms of livestock projections, the model consistently overestimated livestock numbers across all study districts when compared to observed data. In all, the SIMPLACE modelling framework was able to satisfactorily simulate the output of typical MCLS farms.

Furthermore, our findings indicate that under future scenarios, climate change will result in decreased annual rainfall while increasing both minimum and maximum temperatures across all six studied districts. Similarly, grain yields of maize, millet, sorghum, and peanut are anticipated to decline in the near future (2025–2050). Furthermore, livestock numbers are expected to increase in all the study districts, with projections showing over a 100% increase compared to baseline populations. As a result, adaptation strategies such as the adoption of stress-tolerant cultivars, optimization of planting dates, and improved fertilization practices could offer feasible means to mitigate the negative impacts of climate change. Likewise, sustainable grazing land management should be promoted in the study districts and other ecologies facing similar projected increases in livestock populations.

5.2 Recommendations

Overall, results from the meta-analysis indicate that, under different environment and management factors, MCLS likely does not reduce soil GHG emissions compared to arable systems. Therefore, agronomic strategies to better manage applied chemical fertilizer and manure N deposit, must be developed to reduce GHG emission from soils in MCLS. Furthermore, we could not unveil the response patterns of N_2O, CH_4 and CO_2 emissions in MCLS in Africa, Europe and Asia due to differences in system modalities and/or a paucity of published data. This underscores the need for further research to fully understand and quantify the effects of MCLS on GHG emissions at different regions and system types.

Similarly, the survey study was carried out to address the basic question of the impact of fertilizer practices on yield of major crops in MCLS of Burkina Faso and Ghana. This has been achieved, with results improving our understanding of fertilizer practices that may help guide recommended fertilizer management in MCLS of these countries and similar ecologies in West Africa. However, the results have also demonstrated 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. Therefore, farmer's fertilizer practices must not only be based on a calendar date but also on an understanding of manure stoichiometry, crop genotype, soil fertility status, and crop's growth stage.

Furthermore, the results of the model simulation, suggest that overall model performance was satisfactory, as indicated by the relatively low RMSEs. However, the tendency of the SIMPLACE model to overestimate or underestimate grain yields across crop types and study locations highlights the need to fine-tune parameters to account for variability in management decisions (e.g., cultivar selection, planting date), soil fertility status, and weather.

While the data analyzed indicate that grain yields of maize, millet, sorghum, and peanut will decline under future climate conditions and livestock numbers will increase, this effects on smallholder mixed crop–livestock system (MCLS) farmers are not uniform due to diverse resource endowment. As a result, there is the need to characterize household diversity by identifying its main drivers, and adaptation strategies. Hence, to enhance the robustness of future climate scenarios, MCLS studies should employ typology construction to delineate farmer groups with shared characteristics and better capture this diversity.

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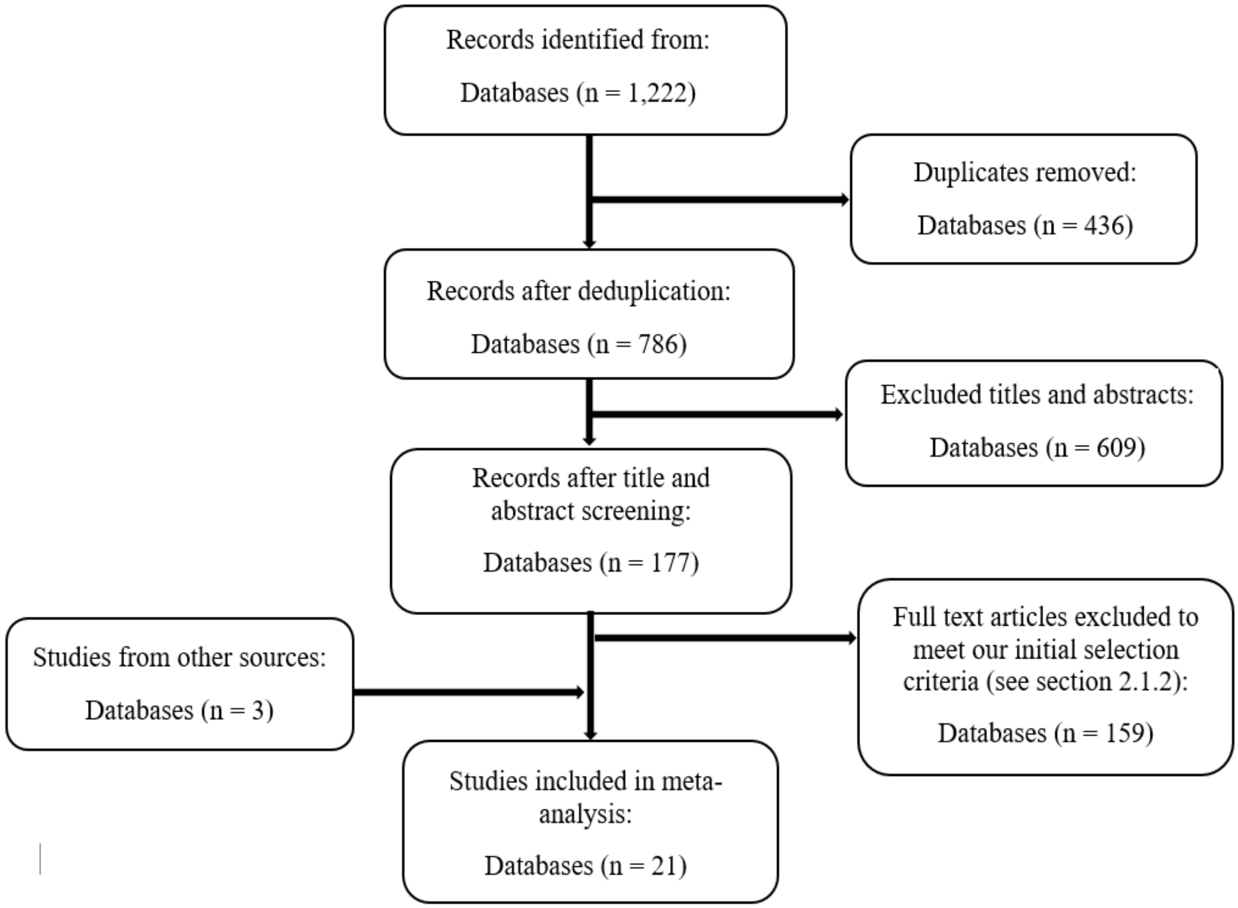
APPENDICES



Appendix 1. PRISMA diagram showing number of articles at each stage of the screening process. Adapted from Moher et al. (2009)

Appendix 2. Description of location, number of observations (NoB), climate, drainage class, crop, and livestock included in this meta-analysis

Study ID	MCLS type	Author (year)	State, Country	Soil GHG(s) measurements			NoB	Drainage class	Fertilizer type	N rate (kg N ha^{-1})	Climate	Crop(s)	Livestock
				N_2O	CH_4	CO_2							
1	Stubble grazing	Liebig et al. (2020)	ND, US	*	--	--	3	moderately well	_	_	Dfb	†Soybean	Cattle
2	Forage rotation	de Carvalho et al. (2022)	DF, BR	*	--	--	2	poor	P_2O_5	_	Aw	†*Panicum maximum*-soybean - sorghum	Cattle
3	Forage rotation	Amadori et al. (2022)	PR, BR	*	*	--	4	moderately well	Urea	90-180	Cfb	†Black oat - corn	Cattle
4	Cover crop grazing	Lazcano et al. (2022)	CA, US	*	*	*	4	moderately well	compost	_	Csb	†Bell beans-cayuse oat-Grape	Sheep
5	Stubble grazing	Barsotti et al. (2013)	MT, US	*	*	*	2	moderately well	Urea	134-252	Dfc	†Wheat	Sheep
6	Forage rotation	Bratti et al. (2022)	SC, BR	*	*	--	2	moderately well	NPK	0	Cfb	†Black oat – corn-soybean	Cattle
7	Forage rotation	Christenson et al. (2021)	NE, US	*	*	--	3	moderately well	Urea	140	Dfb	†Triticale - corn	Cattle

Appendix 2 (continued)

Study ID	MCLS type	Author (year)	State, Country	Soil GHG(s) measurements			NoB	Drainage class	Fertilizer type	N rate (kg N ha^{-1})	Climate	Crop(s)	Livestock
				N_2O	CH_4	CO_2							
8	Forage rotation	Liebig et al. (2021)	ND, US	*	*	--	3	moderately well	Urea, P_2O_5	48	Dfb	†*Thinopyrum intermedium* -corn – soybean – spring wheat	Cattle
9	Forage rotation	Singh et al. (2020)	SD, US	*	*	*	2	moderately well	NPK	140-145	Dfa	†Black oat - corn	Cattle
10	Forage rotation	Pilecco et al. (2019)	RS, BR	*	--	--	6	imperfectly	NPK, Urea	60	Cfa	†Ryegrass-soybean	Cattle
11	Forage rotation	(Abagandura et al., 2019)	ND, US	*	*	*	3	moderately well	_	_	Dwb	†Pea/barley – †corn – cover †crop	Cattle
12	Forage rotation	Piva et al. (2019)	PR, BR	*	*	--	1	moderately well	Urea	0-150	Cfb	†Ryegrass-†black oat - corn	Sheep
13	Forage rotation	de Carvalho et al. (2017)	DF, BR	*	--	--	7	poor	Urea	130-200	Aw	†*Brachiaria brizantha*-soybean - sorghum	Cattle

Appendix 2 (continued)

Study ID	MCLS type	Author (year)	State, Country	Soil GHG(s) measurements			NoB	Drainage class	Fertilizer type	N rate (kg N ha^{-1})	Climate	Crop(s)	Livestock
				N_2O	CH_4	CO_2							
14	Forage rotation	Ribeiro et al. (2020)	SC, BR	*	*	--	1	moderately well	P_2O_5	_	Cfa	†Black oat - soybean	Cattle
15	Forage rotation	Sato et al. (2019)	DF, BR	*	--	--	1	poor	NPK, Urea	100	Aw	†*Brachiaria brizantha* - sorghum	Cattle
16	Forage rotation	da Rocha Junior et al. (2018)	ES, BR	--	--	*	4	moderately well	P_2O_5	_	Aw	†Marandu grass - soybean	Cattle
17	Cover crop grazing	Piva et al. (2014)	PR, BR	*	*	--	1	moderately well	Urea	165	Cfb	†Rye grass-black oat-corn	Cattle
18	Forage rotation	Sato et al. (2017)	DF, BR	*	--	--	2	poor	NPK, Urea	100	Aw	†*Brachiaria brizantha* - sorghum	Cattle
19	Cover crop grazing	Dieckow et al. (2015)	PR, BR	*	*	--	1	moderately well	Urea	90	Cfa	†Black oat - soybean	Cattle

Appendix 2 (Continued)

Study ID	MCLS type	Author (year)	State, Country	Soil GHG(s) measurements			NoB	Drainage class	Fertilizer type	N rate (kg N ha^{-1})	Climate	Crop(s)	Livestock
				N_2O	CH_4	CO_2							
20	Forage rotation	Dhaliwal (2021)	SD, US	*	*	*	1	poor	Urea	67-168	Dfa	†Black oat – soybean - corn	Cattle
21	Forage rotation	Douville (2017)	SD, US	*	*	*	2	poor	_	_	Dfa	†Corn – †soybean – †black oat	Cattle

* Indicates data collected; -- Indicates data not collected; † Indicates main crop used as stubble, forage and cover crop(s); Climate. Köppen-Geiger climate classification: Aw = tropical savannah with dry winter; Af = tropical rainforest, fully humid; Cfa = humid subtropical; Cfb = temperate oceanic; Csb = warm-summer Mediterranean; Dfa = hot-summer humid continental; Dfb = warm-summer humid continental; Dfc = subarctic climate; Dwb = monsoon-influenced warm-summer humid continental.

Appendix 3. Country and crop specific timing for chemical fertilizer application considered in this study

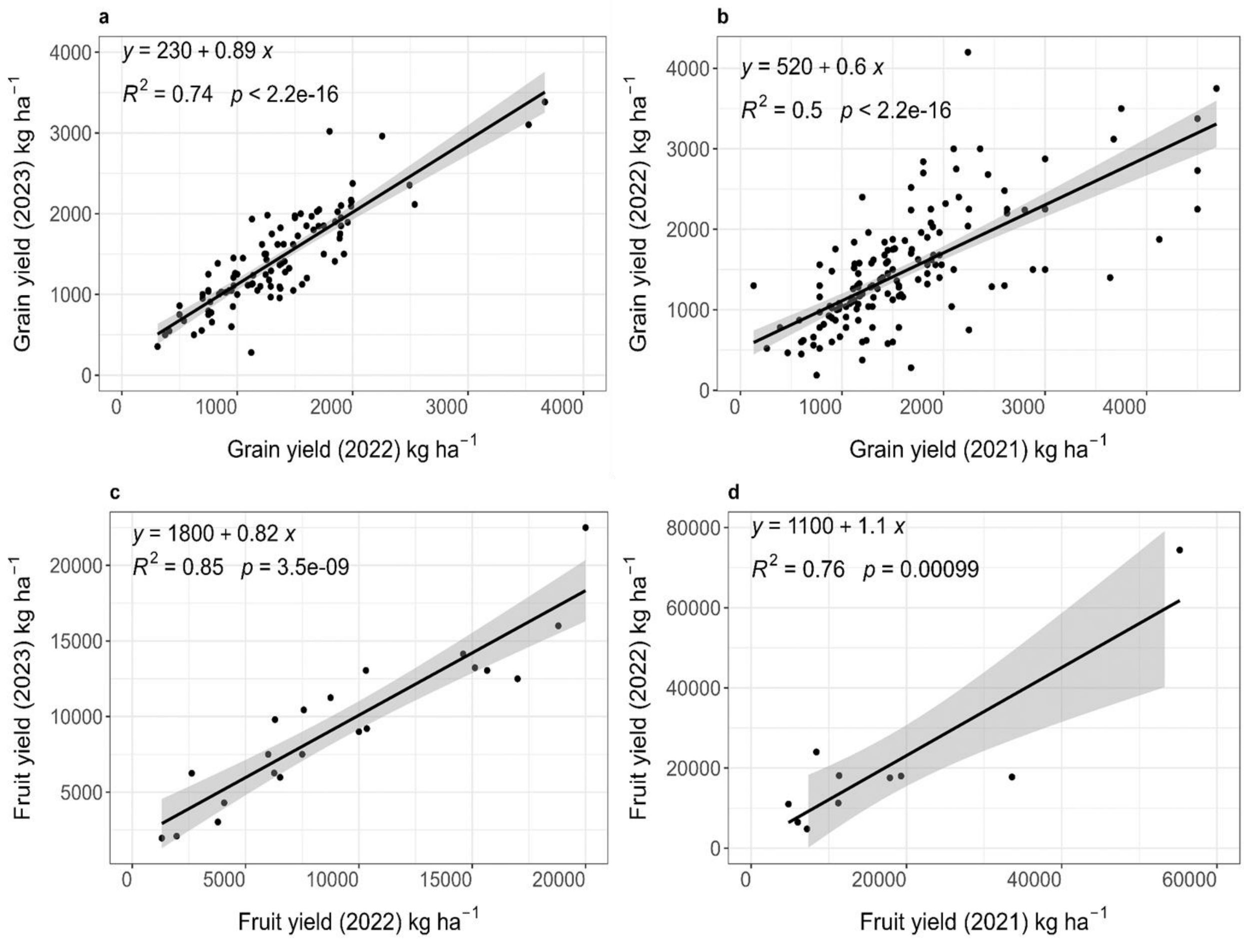
Timing of chemical fertilizer application (in days)			
		Burkina Faso	
Crop type	Optimum	Late	Reference
Maize	≤ 15 DAP	> 15 DAP	Saba et al. (2023)
Sorghum	≤ 14 DAP	> 14 DAP	Palé et al. (2009); Ouedraogo et al. (2022)
Millet	≤ 14 DAP	> 14 DAP	Yameogo et al. (2022)
Peanut	≤ 7 DAP	> 7 DAP	Bado et al. (2013)
Cowpea	≤ 7 DAP	> 7 DAP	Bado et al. (2013)
Green beans	≤ 7 DAP	> 7 DAP	Bado et al. (2013)
Tomato	≤ 14 DAT	> 14 DAT	Konfe et al. (2019); Coulibaly et al. (2021)
Onion	≤ 14 DAT	> 14 DAT	Sawadogo et al. (2022)
Egg plant	≤ 14 DAT	> 14 DAT	Konfe et al. (2019)
		Ghana	
Maize	≤ 14 DAP	> 14 DAP	Adu Boakyewaa et al. (2014)
Rice	≤ 14 DAP	> 14 DAP	Dogbe et al. (2015)
Sorghum	≤ 7 DAP	> 7 DAP	Buah et al. (2012)
Millet	≤ 14 DAP	> 14 DAP	Kanton et al. (2015)
†Peanut	N.A	N.A	-
†Cowpea	N.A	N.A	-
†Soybean	N.A	N.A	-
Tomato	≤ 14 DAT	> 14 DAT	Agyeman et al. (2021)
Pepper	≤ 14 DAT	> 14 DAT	Adimassu et al. (2020)

†Timing of chemical fertilizer application was not applicable in this study. DAP = Days of planting, DAT = Days of transplanting.

Appendix 4. Country and crop specific N rate (kg/ha) recommendation considered in this study

N rate applied (kg/ha)			
Burkina Faso			
Crop type	Low	Recommended	Reference
Maize	< 68.5	≥ 68.5	Theriault et al. (2018)
Sorghum	< 30.0	≥ 30.0	Palé et al. (2009)
Millet	< 37.0	≥ 37.0	AGRIDATA (2019); Yameogo et al. (2022)
Peanut	< 14.0	≥ 14.0	Bado et al. (2013)
Cowpea	< 14.0	≥ 14.0	Ishikawa et al. (2013); Bado et al. (2018)
†Green beans	< 14.0	≥ 14.0	Bado et al. (2018)
Tomato	< 95.0	≥ 95.0	Coulibaly et al. (2021)
Onion	< 112.0	≥ 112.0	Garane et al. (2019)
Egg plant	< 72.0	≥ 72.0	Sawadogo et al. (2022)
Ghana			
Maize	< 90.0	≥ 90.0	Adu Boakyewaa et al. (2014); Moahmmed et al. (2023)
Rice	< 90.0	≥ 90.0	Moro et al. (2008); Dogbe et al. (2015)
Sorghum	< 40.0	≥ 40.0	Buah et al. (2012)
Millet	< 40.0	≥ 40.0	Kanton et al. (2015)
Peanut	< 20.0	≥ 20.0	Essilfie (2019); Mintah et al. (2020)
Cowpea	< 20.0	≥ 20.0	Adzoyi (2015); Mintah et al. (2020)
Soybean	< 20.0	≥ 20.0	Adzoyi (2015); Kermah et al. (2022)
Tomato	< 90.0	≥ 90.0	Amankwaa-Yeboah et al. (2023)
Pepper	< 173.0	≥ 173.0	Adimassu et al. (2020)

† Due to the limited data on the recommended nitrogen (N) rate for this crop type, we applied the rates established for other legumes in the country



Appendix 5. Variations between reported yields (farmer's response) and measured yields for grain crops in Burkina Faso (a) and Ghana (b), and for vegetable crops in Burkina Faso (c) and Ghana (d). Solid line through the data points is a regression line.

Appendix 6. Construction of 25m^2 yield plots for pepper (left) and peanut (right) in MCLS fields

Appendix 7. Data on average weight for the different age classes of poultry is being collected for chicks (top right), sub-adult (bottom right) and adult (left)

Appendix 8. Data on average weight for the different age classes is being collected for each of the various livestock (from left to right); goat, sheep, cattle, and pig.

Appendix 9. Comparison of simulated and observed average crop yields at study locations

Country	District/commune	Crop	Yield		MR (%)	BQ
			Observed	Simulated		
Ghana	Bongo	Maize	1554.23	1738.67	11.86	-184.44
		Millet	1260.89	1105.34	-0.12	155.53
		Sorghum	1247.08	1560.92	0.25	-313.83
		Peanut	1483.03	1192.21	-0.19	290.82
	Builsa North	Maize	1546.66	1727.54	11.69	-180.87
		Millet	1313.96	1049.77	-0.20	264.18
		Sorghum	1500	1632.99	0.08	-132.99
		Peanut	1063.75	1067.85	0.00	-4.10
	Kassena Nankana	Maize	1950.33	1634.73	-16.18	315.59
		Millet	1091.25	1014.75	-0.07	76.50
		Sorghum	1225	1559.11	0.27	-334.11
		Peanut	1067.50	1129.38	0.05	-61.88

Appendix 9 (continued)

Country	District/commune	Crop	Yield		MR (%)	BQ
			Observed	**Simulated**		
Burkina Faso	Loumbila	Maize	1526.46	1868.79	22.42	-342.33
		Millet	437.50	360.00	-0.17	77.49
		Sorghum	1246.17	1328.70	0.06	-82.53
		Peanut	1086.08	1012.75	-0.06	73.33
	Ziniaré	Maize	1873.76	1868.79	-0.26	4.96
		Millet	808.33	720.01	-0.10	88.31
		Sorghum	908.15	1328.70	0.46	-420.55
		Peanut	1233.68	1012.75	-0.17	220.93
	Zitenga	Maize	1501.1	1385.47	-11.19	174.62
		Millet	1406.80	1345.46	-0.04	61.33
		Sorghum	1142.47	1077.51	-0.05	64.96
		Peanut	1337.30	774.78	-0.42	562.52

Appendix 10. Comparison of simulated and observed livestock numbers at study locations

		Livestock numbers			
Country	**District/commune**	**Observed**	**Simulated**	**MR (%)**	**BQ**
Ghana	Bongo	103.15	143.18	0.38	-40.03
	Builsa North	70.2	118.90	0.69	-48.70
	Kassena Nankana	114.78	150.02	0.31	-35.24
Burkina Faso	Loumbila	86.58	91.15	0.05	-4.70
	Ziniaré	86.45	91.15	0.05	-4.70
	Zitenga	64.19	74.41	0.15	-10.22

POLICY BRIEF

Executive Summary

Mixed crop-livestock systems (MCLS) are central to food security in the Sudan Savannah region of West Africa. However, these systems are increasingly vulnerable to climate change. The present study assessed the impact of climate change on MCLS productivity in Ghana and Burkina Faso using systematic reviews, field surveys, and crop-livestock modeling. The findings highlight significant yield losses for staple crops and a sharp increase in livestock numbers, with implications for both food production and environmental sustainability. Adaptation strategies must prioritize climate-smart fertilizer practices, improved crop and livestock management, and sustainable grazing land management.

Background

In Sub-Saharan Africa, diversified MCLS provide vital services including food, income, and nutrient cycling. However, rising temperatures, erratic rainfall, and land degradation threaten their productivity. Understanding how climate change affects both crop and livestock components is essential for developing integrated and context-specific adaptation strategies.

Key Findings

Soil Greenhouse Gas Emissions: Meta-analysis revealed that drainage class, stocking density, climate, nitrogen fertilizer rate, fertilizer type, and soil texture are key drivers of GHG emissions in MCLS.

Fertilizer Practices: Country-specific recommended nitrogen rates and fertilizer source significantly improved grain and vegetable yields, particularly in Ghana.

Model Calibration: The SIMPLACE modeling framework was used to simulate crop and livestock productivity. Model validation showed satisfactory performance with a mean residual error (MR) ranging from -12% to +18% for crops and 27% for livestock.

Future Projections (2025-2050):

The results demonstrate that in the future (2025-2050), there will be a significant decline in maize (up to -34%), millet (up to -57%), sorghum (up to -53%), peanut (up to -23%) grain yields, and a significant increase in livestock numbers (up to 181%).

Policy Recommendations

1. Nutrient management: Support adoption of best fertilizer management practices including appropriate rates, placement, timing, and amount.

2. Stress tolerant Varieties: Develop and disseminate drought- and heat-tolerant varieties suitable for diverse MCLS environments.

3. Management of grazing lands: Develop sustainable livestock grazing systems to balance projected herd increases with declining grass/forage availability.

4. Indigenous knowledge: Strengthen advisory services to guide farmers in adapting to changing climatic conditions. the co-creation of knowledge that brings together all stakeholders, especially indigenous knowledge of local farmers, should be the central element for creating a locally adapted, sustainable and transformative MCLS.

5. Integrated Modeling Tools: Use validated integrated simulation models that couples different aspect of MCLS to develop sustainable agricultural practices in response to climate change.

Conclusion

The productivity of MCLS in the Sudan Savannah of West Africa is at risk due to projected climate changes. As a result, crop yields are expected to decline significantly while livestock numbers are likely to see a rise, creating resource management challenges. Policymakers must act swiftly to implement climate-smart adaptation strategies that ensures climate mitigation, resilience whiles sustaining crop yields and livestock productivity