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LETTER

Crop-livestock-climate nexus: intensification pathways under different climate realizations in the Sahel, West Africa

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Abstract

Competition between crops and livestock farming systems escalates due to changing land use patterns driven by climate change in the Sahel of West Africa's, particularly the Volta and Niger River basins. This study demonstrates the practical implications of sustainable intensification pathways under different climate realizations that illustrate the synergies of the crop-livestock-climate nexus in reducing the negative impacts of climatic extreme events in the Sahel of West Africa. Integrated crop-livestock experimental designs were conducted during the 2018–2022 rainy seasons across Burkina Faso, Ghana, Mali, and Niger and covering 80 pilot farms across these countries. These pilot sites were grouped into intensive and extensive sets. The intensive pilot sites implemented Fisher block experiments under natural conditions, with multiple treatments involving the use of digestate from biodigesters. The extensive sites employed a randomized complete block design with treatment involving compost from pits/surfaces. To support these experimental designs, a customized agroclimatic information package was provided to the farmers in the pilot sites. The package included sub-seasonal-to-seasonal forecasts and agricultural advisory of how the climate information can be used efficiently (i.e., Technical itinerary). *Results* indicate that amendments significantly impacted soil nutrient levels, with compost from pits exhibiting superior carbon storage despite recorded weather extremes. Organic fertilization increases nitrogen content, compensating for plant nitrogen exports. Furthermore, digestate-based and pit compost effectively enhance soil fertility in terms of carbon, phosphorus, and nitrogen. Crop production also showed marked improvements, particularly in treatments receiving organic amendments and micro-doses of chemical fertilizers, although variations between sites were evident. Hence, two basic intensification pathways were identified that emphasize using crop residues, composts, and agroclimatic information advisory systems, presenting scalable solutions for sustainable agricultural development and climate resilience in the Sahel region. Integrating biodigester technology, composting, and micro-dosing practices provides short and medium-term benefits, including improved soil health, enhanced water retention, and greater resilience to climate extremes. This sustainable approach is scalable and also addresses waste management and emission reduction, aligning with climate-smart practices. To promote such mixed farming systems agricultural policies must include awareness campaigns about these pathways, subsidies for the biodigester technology, and technical training to farmers in the Sahel region.

1. Introduction

The relatively recent climate challenges in the West African region include increasingly extreme rainfall events and flooding episodes (Taylor *et al* 2017, Salack *et al* 2018), which result in soil waterlogging issues, nutrient leaching, and erosion (Daku *et al* 2022, Folberth *et al* 2014). In the smallholder farming system, the erratic distribution of rainfall events leads to higher rates of re-planting, post-flowering water stress of up-land crops, flooding and water-logging of lowland cereals. The potential nutrient depletion of arable land including micronutrients due to nutrient leaching, water erosion is higher as a result of intense rainfall events (Folberth *et al* 2014), and has been shown to lead to significant losse of soil nitrogen stocks (Zhou *et al* 2014). At the same time soil fertility restoration during the short fallow periods is insufficient (Srivastava *et al* 2012, Gaiser *et al* 2011). The increase in temperatures leads to heat stress, increases evapotranspiration rate, increases crop water demand, hampers - floral development, hastening of crop maturity and reduces crop productivity (Salack *et al* 2015, Rezaei *et al* 2015).

To enhance resilience, rural communities in the Volta and Niger river basins pursue various livelihood strategies, including rainfed agro-pastoralism, market-gardening in lowlands, government-built irrigation schemes, small-scale irrigation based on small reservoirs and river and groundwater pumping, fishing, and agroforestry. However, there is a need for further efforts to achieve sustainable intensification of their primary livelihoods. In the face of the new climate challenges (IPCC 2023), sustainable smallholder farming needs to include climate-smart, site-specific practices combining crop and livestock productions to support sustainable intensification (Thornton and Herrero 2015), increase water and nutrient use efficiencies and to further close the nutrient cycles. To address the climate challenge and resilience effectively, smallholder farmers require two keys elements. Firstly, they require reliable predictions regarding the onset and cessation of the rainy season, along with information on intra-seasonal dry spells, wet spells, and extreme rainfall events (Salack *et al* 2016, Waongo *et al* 2014, Laux *et al* 2008). Secondly, they must explore and adopt various agrotechnological innovations that can simultaneously support crop and livestock productions while carefully managing trade-offs and synergies between these two critical income-generating systems under different and adverse climate conditions (Liersch *et al* 2023).

However, crop-livestock systems are characterized by many interacting factors exacerbated by shifts in land use patterns due to climate change. Therefore, innovative research tools are needed to design options for crop-livestock integration while taking into account the perspectives of the local stakeholders to cope with climate constraints and economic viability. The concept of the crop-livestock-climate nexus revolves around understanding and addressing the interactions and interdependencies between these systems to promote sustainable and resilient productivity, thereby enhancing regional food security. It encompasses how these three elements interact and influence each other within agricultural ecosystems. The climate variables such as rainfall patterns, temperature, and extreme weather events profoundly impact both crop and livestock systems, while in turn, the management and practices associated with these systems can influence the local climate and environment through their local carbon footprint to the atmosphere (Srisvatava *et al* 2025).

Understanding the crop-livestock-climate nexus is essential for developing sustainable and resilient agricultural practices, particularly in regions prone to climate variability and change such as semi-arid areas. This paper defines and demonstrates the practical implication of two major intensification pathways under different and adverse climate conditions, land use practices, and land cover types in the semi-arid regions of the Volta and Niger River basins in West Africa. These pathways demonstrate the synergies in the crop-livestock-climate nexus to reduce greenhouse gas (GHG) emissions while optimizing soil water availability, nutrient retention, and the negative impacts of climatic extremes. The network of demonstration sites, farms, biodigesters, compost pits, agroclimatic information package delivered, and the experimental designs are decribed in section 2. The results and analized and discussed in sections 3 & 4 respectively before the concluding remarks found section 5.

2. Materials and methods

2.1. Observation transect

An observation network covering diverse climatic zones across Burkina Faso, Ghana, Mali, and Niger, was established along a transect that stretched from the upper Niger Basin to the Northern Volta Basin, following a North-South and East-West gradient. With a collaborative and multidisciplinary approach involving agricultural extension services, farmers, research scientists, and technicians (including meteorologists, soil scientists, socio-economic scientists, and agronomists), we identified 80 pilot farms. These farms were distributed as follows: 42 in Burkina Faso, 20 in Ghana, 8 in Niger, and 14 in Mali. The sites in Mali were also involved in documenting endogenous knowledge and adaptation practices that could complement and

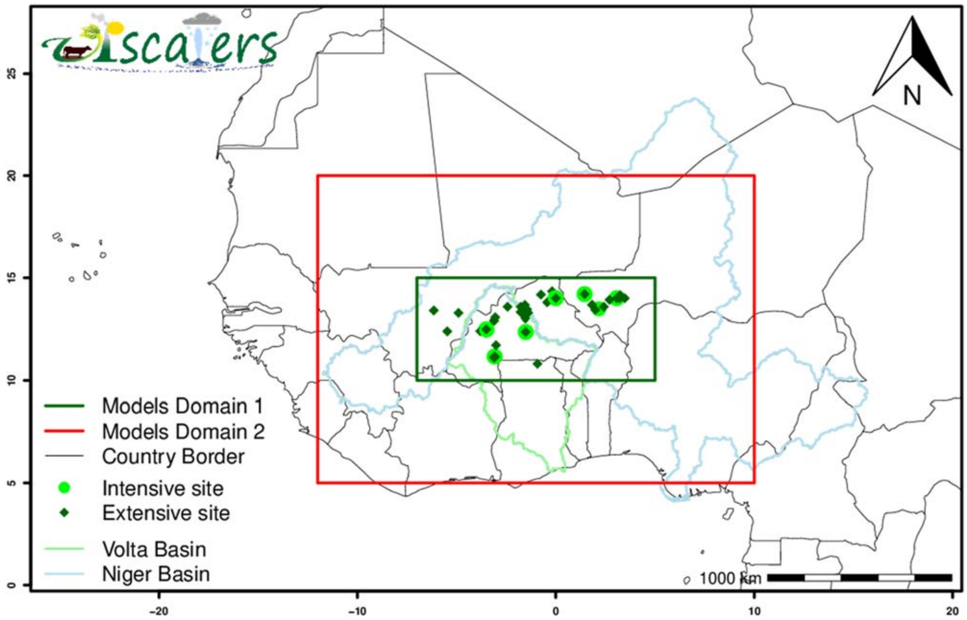

Figure 1. Location of the case study transect (highlighted in green) within the Volta-Niger River basins. The outer red box represents the model domain, while the inner green box indicates the observation transect with intensive and extensive pilot farms. Green dots signify areas where biodigesters are implemented, and black dots symbolize regions where compost pits have been implemented. In Mali, indigenous knowledge was documented to complement research data.

strengthen research and field extensions. The remaining pilot sites were categorized into intensive and extensive sites.

Figure 1 depicts the location of the observation transect within the Volta-Niger River basins (the inner green box). Green dots indicate intensive pilot sites where biodigesters were implemented, while black dots represent the extensive pilot sites where manual compost-making processes were employed. Seven intensive sites (four in Burkina Faso and three in Niger) were equipped with biodigesters to produce biogas and slurry compost (i.e., the digestate) for soil improvement. In contrast, 65 extensive sites were established across Burkina Faso (41 sites), Ghana (10), and Mali (14), featuring pit or surface compost production facilities that transformed animal and crop residues into compost.

From the designated pilot sites, the datasets included crop by-products (e.g., crop yield, biomass), soil samples (collected before, during, and after experiments), compost samples (from pits or surface), digestate and AgInfo. To maintain the quality of collected data, all physicochemical laboratory analyses of samples were carried out by the National Bureau of Soil Analyses of Burkina Faso (BUNASOL). Details regarding sampling and samples analyses are given in the appendix.

2.2. Composts production network

Our study involves two types of compost: a traditional compost obtained manually through surface or pits composting, referred to as 'compost and 'the digestate, a product from biodigesters.

The biodigester, a semi-buried masonry structure plays a pivotal role in our research (figure 2). It primary purpose is to facilitate the anaerobic conversion of organic materials, including animal manure (such as cow and pig manure), into valuable biogas. In Burkina Faso, various models of biodigesters have been developed and promoted. For this study, the Faso Bio-15 (FB-15) model (figure 2) was installed at the intensive sites. The FB-15 biodigester has a capacity of 4 m^3 and can produce up to 42 tons of digestate annually. It operates by utilizing animal feces from the stalls as feedstock, to generate both digestate and biogas. These outputs are then utilized as inputs for crop production, contributing to carbon sequestration in the soil. The FB-15 model is endorsed by the *Programme National Biodigesteur* (PNB-BF) of Burkina Faso, which aims to distribute biodigesters throughout the country (https://www.pnb-bf.org/). The PNB-BF initiative has led to the creation of '*Alliance pour le Biodigesteur pour l'Afrique de l'Ouest et du Centre*" to expand the distribution of bidigesters in West and Central Africa (https://ab-aoc.org/).

The sixty-five compost production sites, designated as extensive pilot sites, employ aerobic conditions to decompose crop residues or animal waste. This process involves layering 5 cm of chopped crop residues and manure in a pit or on the surface, subsequently covering it with plastic sheets to create anaerobic conditions. Regular watering was carried out to maintain optimal humidity levels conducive to organic matter

Figure 2. Completed construction of a biodigester (left) and a training session for recipients in Dano (Burkina Faso) and Bonkoukou (Niger) pilot sites. The slurry compost produced by the biodigester is used to support maize and millet production on the farm during all the rainy seasons.

decomposition. The internal temperature was monitored, and the piles are renewed every two weeks until the final compost was obtained, typically within 3–4 months. Farmers undertake this manual compost-making technique before the onset of the rainy season, which usually occurs between March and May each year. Extension agents and technicians involved in integrated crop-livestock experiments at the pilot sites provide guidance and supervision throughout the process, to ensure correct production of compost.

2.3. Integrated crop-livestock experimental designs

During the rainy seasons from 2018 to 2022, two types of experiments were conducted at pilot sites under natural conditions. In the intensive sites, a Fisher block experiment was established, featuring five (5) treatments replicated four times. These treatments included:

- T0.0—Control
- T0.1 - Treatment with digestate-based compost
- T0.2 - Treatment with digestate-based compost and microdoses of mineral fertilizer
- T0.3 - Treatment with compost from pits/surface
- T0.4 - Treatment with compost from pits and microdoses of mineral fertilizer

Each plot measured 122 m^2 with a 1 m spacing between them (figure 3). In the intensive sites located in Dano and Boassa, Burkina Faso, we tested maize (Espoir cultivar with a 95-day sowing cycle) and sorghum (Kapelga variety with a 100–105-day cycle), respectively. The treatments were combined into three fundamental intensification scenarios. The first was the '*Control*' (no input control of organic and mineral fertilizers). The second and third consisted of the '*intensification*' scenarios based on the use of the '*digestate*' (with and without mineral ferilizer), and '*compost*' (with and without mineral fertilizer). Each plot received an application of 5 tons ha^{-1} of compost. For inorganic fertilizer, 100 kg ha^{-1} of NPK (with a formula of 14–23–14) were applied in Boassa and Dano, respectively, 14 days after sowing. Furthermore, 45 days after sowing, 150 kg ha^{-1} of urea (with a 46% N content) were applied in these two areas. The crop density were 18,000 plants ha^{-1} for Boassa and 30,000 plants ha^{-1} for Dano.

In the extensive sites, a randomized complete block design with three treatments was implemented, repeated four times (figure 3). These treatments comprised a control group, a compost-only treatment, and a compost-

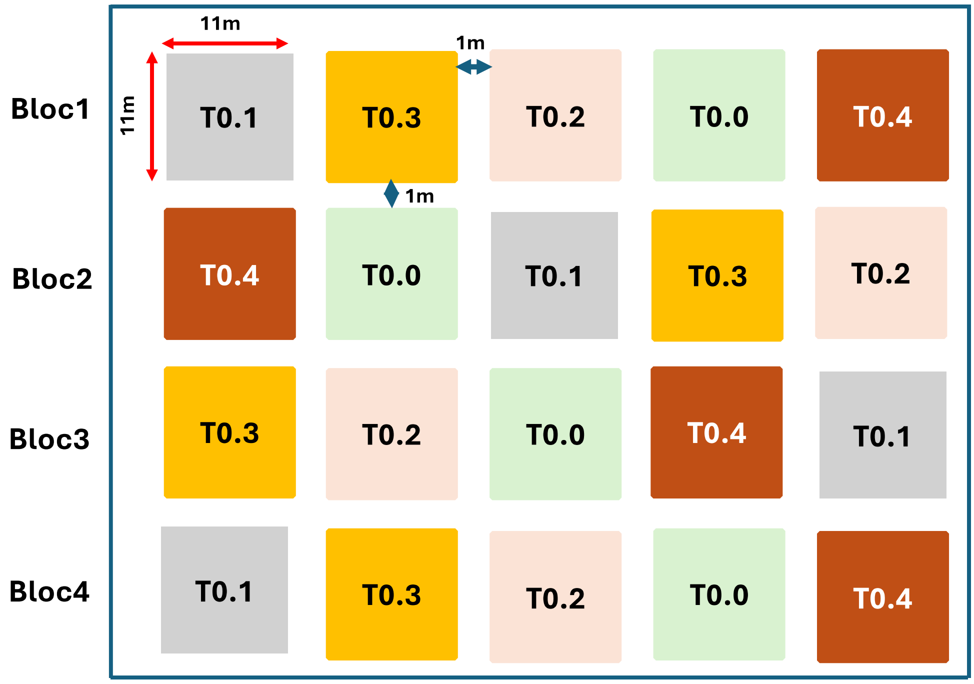

Figure 3. Experimental design on intensive sites (T0.0: control; T0.1: treatment based on compost from the biodigester; T0.2: treatment based on compost from the biodigester + chemical fertilizer; T0.3: treatment based on compost from a pit/surface; T0.4: treatment based on compost from pit + chemical fertilizer).

mineral manure treatment. To support these experimental designs, a customized agroclimatic information package was provided to the farmers in the pilot sites.

Before establishing the intensive demonstration and extensive pilot sites, a screening and focus group discussions were conducted to ensure that the selected farmers met the desired criteria, which included: i) Land ownership, ii) Farmer's willingness to share his/her crop area for demonstration, iii) Availability of livestock (at least 6 herds), iv) Easy access to water and market, v) Farmer's willingness to participate and his/her ability to participate in co-financing the experiment at 5%–10% of the biodigester installation cost).

2.4. Agroclimatic information delivery

In recent years, the rainy seasons in the Sahel have exhibited a mixed pattern, including intense rainfall, strong winds, and intra-seasonal long dry spells (Salack *et al* 2016, Taylor *et al* 2017). This erratic distribution of rainfall poses significant challenges for smallholder farming systems, leading to higher rates of re-planting, post-flowering water stress, flooding, and soil waterlogging. The intense rainfall events contribute to nutrient depletion through leaching and erosion, leading to the depletion of soil nitrogen stocks. Rising temperatures exacerbate heat stress, increase crop water demand, hinder floral development, accelerate crop maturity, and reduce productivity. Climate projections indicate a worrisome increase in the frequency and intensity of extreme events in the 21st century (Salack *et al* 2022, IPCC 2023).

To enable the access and use of climate information farming practices, an agroclimatic information package (referred to as the AgInfo package) was delivered to the farmers in the pilot sites during the rainy seasons (figure 4). The weekly AgInfo package includes georeferenced information about pilot farms and pre-existing physical features (e.g., surface area, soil type, slopes). The message provides a seasonal forecast for the next three months, a 24-hour forecast, a deterministic seven-day forecast for extremes events (e.g., False onset, Heavy rainfall, Extreme dry spells, Early Cessation), and agricultural practice instructions in relation to the forecasts in the form of 'technical itineraries' (Sanfo *et al* 2022). The package is generated on a single day and is valid for a week. The technical itineraries are customized based on the crop type (e.g., maize, millet, sorghum, and cowpea), growth stage, and forecast information. It also contains verification skill scores and focuses on issues such as the *'False onset of the cropping season'*, *'10-day dry spells'*, and the three categories of heavy rain events namely category 1 (37–65 mm per day), category 2 (65–85 mm per day), and category 3 greater than 85 mm per day (Salack *et al* 2018).

The package is delivered to users through their mobile phones as voicemail messages and is translated into local languages, including Mooré, Dagara, Fara-Fara, French, and English. To monitor and evaluate the performance of the AgInfo package, an Agro-climatic Field School (AFS) animation is organized twice a season

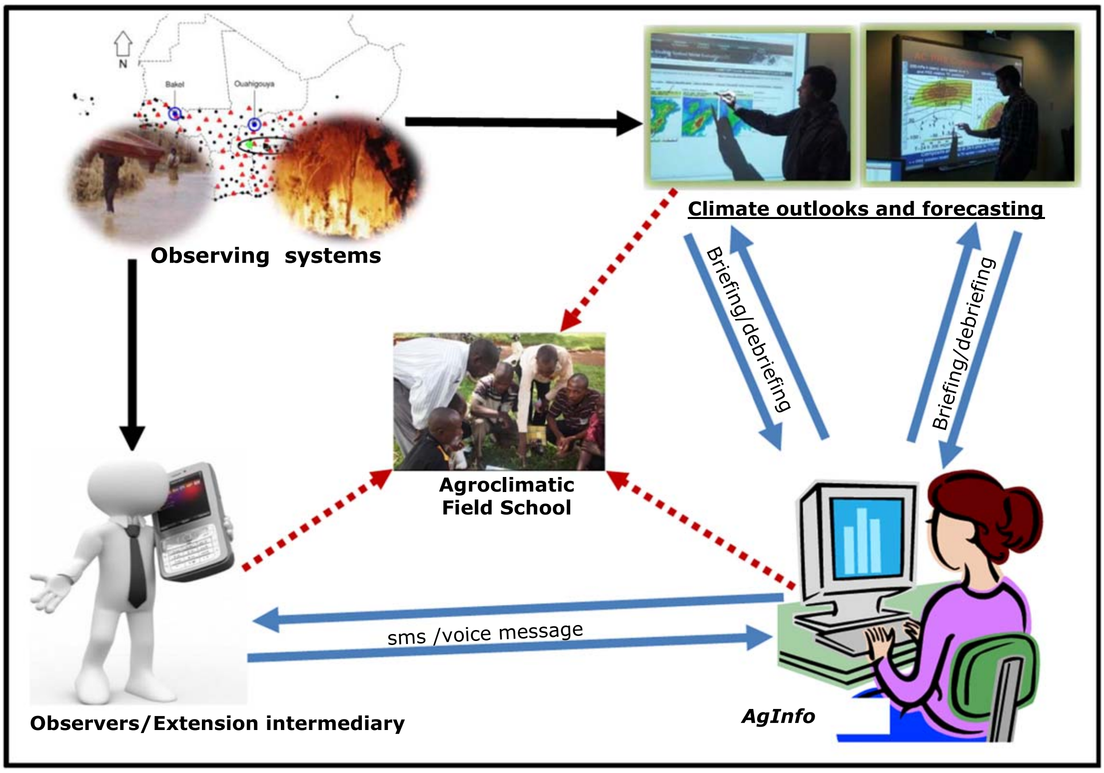

Figure 4. Conceptual framework of Agroclimatic information (AgInfo) package production and and interaction among stakeholders.

with the beneficiaries. The AFS involves personalized interview sessions with the farmers, either via telephone or face-to-face, to discuss the content of AgInfo, its understanding, and its use. The AFS also includes other relevant aspects not covered in the AgInfo package, such as local climate past and future trends, variability, crop pests, and diseases, etc Furthermore, farmers actively participate in verifying the quality of the AgInfo package immediately after receiving it and during the AFS sessions to help identify failures and document the accuracy of the information. These AFS sessions are organized and scheduled two months after planting to provide timely support and guidance after and before the key stages of the crop cycle. Whilst, the AFS sessions organized one month after harvest after the rainy season are designed to evlaute the success and failure of the AgInfo delivery, stocktake farmers experience of the season, and prepare for further post-harvest activities (Sanfo *et al* 2022).

3. Results

3.1. Soil amendments

The graphs shown in figure 5 illustrates the nutrient levels in the soil before and after the trials were conducted. The mineral elements analyzed during these years of experimentation are Carbon, Nitrogen, Phosphorus, and Potassium.

Carbon storage in the soil is significantly influenced by the amendments. Compost from the pit promoted better carbon storage compared to compost from the biodigesters. In terms of nitrogen, it was evident that the nitrogen content in the various plots where organic fertilization was applied showed a substantial increase since 2019. Meanwhile, the absolute control group (T0) has experienced a marked decrease in nitrogen content. This decrease can be attributed to the fact that the added organic matter was rich in nitrogen, compensating for the plant's nitrogen exports, while the control plot became depleted of nitrogen. The plots benefiting from the biodigesters have, on average, slightly higher nitrogen content than those with the pile compost.

The dynamics of phosphorus in the soil were slightly different from those of nitrogen. The plots with digestate have, on average, lower phosphorus content in the soil compared to the plots that received compost from the manual compost-making process. In the plots amended with compost from the biodigesters, the phosphorus content is significantly higher in the soil when associated with chemical fertilizer, while the opposite effect occurs with pile or pit compost. Naturally, there was more pronounced depletion in the unfertilized control plots (figure 5).

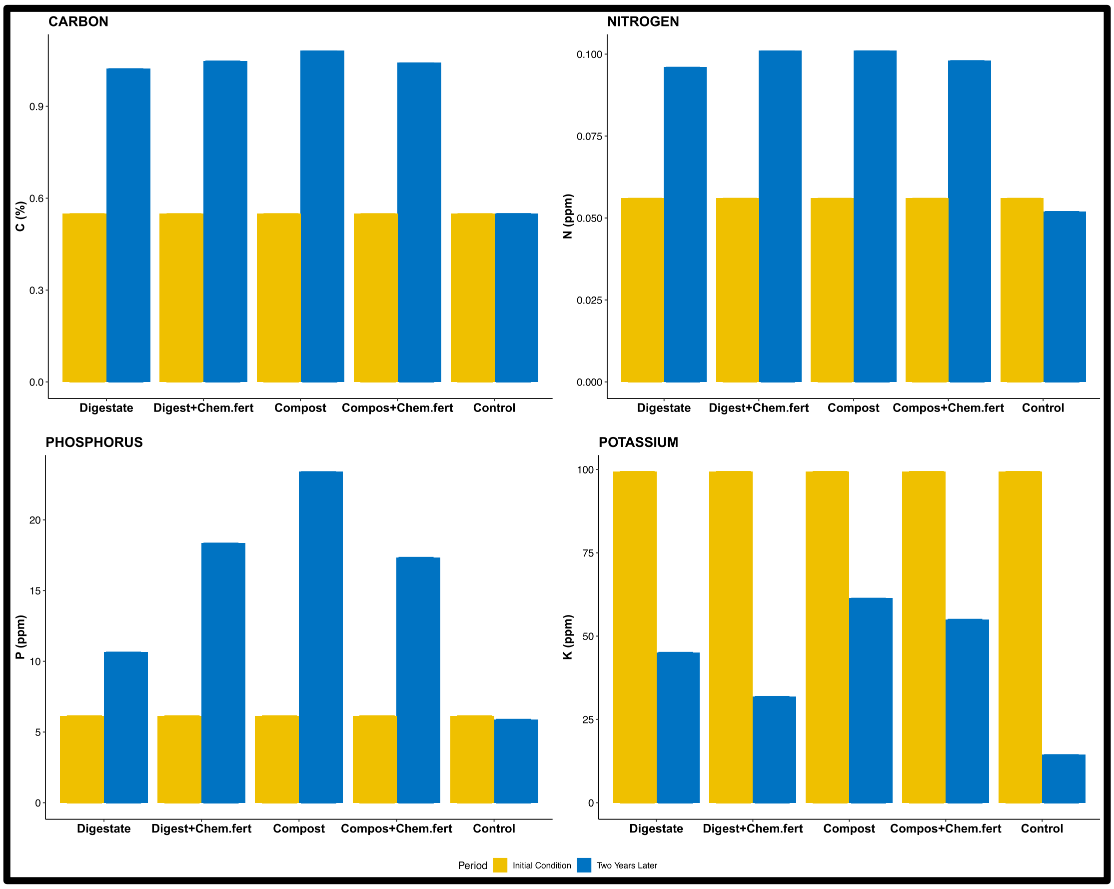

Figure 5. Aggregated dynamics of mineral elements in the soils of the Boassa and Dano pilot sites.

The plots amended with digestate-based compost had lower potassium content compared to those with compost from pits.

The application of digestate-based and pit compost significantly improved the soil's chemical fertility in terms of mineral elements over time, particularly Carbon, Phosphorus, and Nitrogen. Similarly, Wang *et al* (2023) demonstrated that digested-based compost can provide essential nutrients such as nitrogen, calcium, magnesium, and organic matter to the soil. . While the amendment did not significantly increase the quantity of potassium, it did help limit its decrease compared to the control. The overall decrease in potassium content in the plots may be due to significant uptake by both sorghum and maize planted at Boassa and Dano. However, the lower potassium levels in plots that received a combination of inorganic fertilizer and compost could be attributed to leaching and microbial competition. The decomposing organic matter in the compost can stimulate microbial activity, potentially leading to potassium being temporarily immobilized in microbial biomass. Potassium is a critical mineral element that plays a vital role in shielding plants against water stress by limiting transpiration. It is readily available to plants as most of its forms are soluble and assimilable.

3.2. Crop production levels

Figure 6, presented below, provides an overview of the biomass and yield of sorghum and maize observed in on-farm experiments. Notably, the plots that received fertilization consistently displayed the best performance in terms of yields, especially in the scenario where compost from pits is combined with micro-doses of chemical fertilizers. This remarkable increase in yield was particularly evident at the Dano site. However, at the Boassa site, a different trend was observed, with the performance of the compost from pits associated with organic manure experienced a decline, eventually reaching the levels of treatments without such associations. In the treatments that received compost without micro-doses of chemical fertilizers, the difference in yields between the digestate-based and traditional compost was not as pronounced. Recent findings have highlighted that Digestate-based compost, when used in excess beyond a certain threshold, can actually inhibit growth according to the laboratory experiments conducted by Wang *et al* (2023). This underscores the significance of maintaining a proper nutrient balance. Nevertheless, we did observe a slight superiority of digestate over manual compost in terms of average yields at Boassa, with the opposite trend observed at Dano.

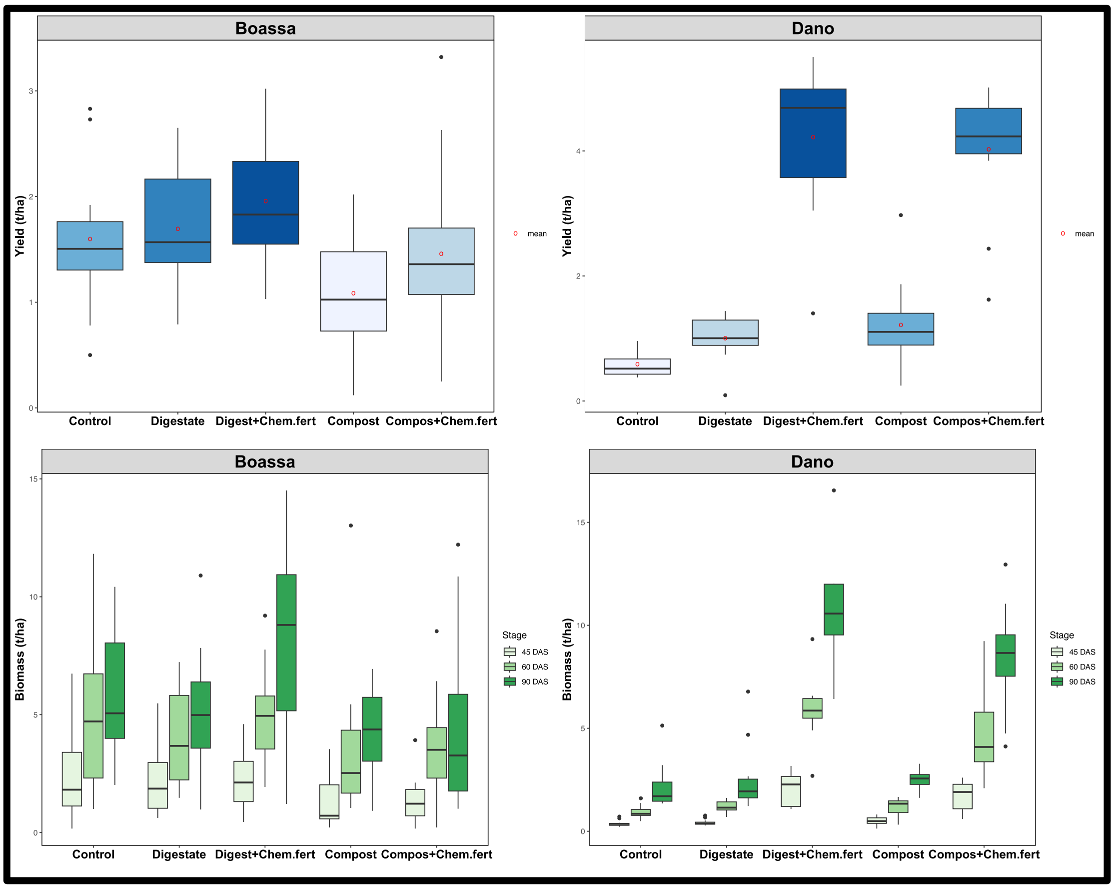

Figure 6. Aboveground biomass and yield levels of sorghum (Boassa) and maize (Dano) under different fertilizations scenarios based on the intensification pathways during the 2018–2022 campains of the rainy season.

When we delve into grain yields and dry biomass, it becomes apparent that the plots receiving the digestate from the biodigester and pit compost consistently outperformed the control group. These findings corroborate the conclusions drawn by Koulibaly *et al* (2009), who demonstrated noticeable improvements in yields following compost applications. According to these authors, compost not only supplies essential mineral elements to the plants but also contributes significantly to enhancing soil conditions, which, in turn, favor the optimal development of plants.

Expanding on related research, Bationo & Buerkert (2001) and Wang *et al* (2023) have delved deeper into the subject. They emphasize that improved root penetration, enhanced photosynthesis, increased soil moisture retention, and heightened biological activity within the soil all play pivotal roles in driving yield improvements resulting from the application of organic matter. These studies collectively underline the significant potential of organic amendments like compost in enhancing crop yield.

4. Discussion

4.1. Climate challenges and resilience

The recent climate challenges faced by West Africa's Sahel region, including extreme rainfall events, erratic rainfall patterns, and increased temperatures, have been well-documented in previous studies (Taylor *et al* 2017, Laux *et al* 2008). These climate anomalies have resulted in soil waterlogging, nutrient leaching, and erosion, which adversely affect crop and livestock production. The use of customized agroclimatic information such as AgInfo package has proven to be an invaluable resource, offering critical insights into the timing, duration, and intensity of rainfall patterns. This information empowers agro-pastoralists to make well-informed decisions regarding cropping systems, livestock management, and water resource allocation. In the water-scarce Sahel region, customized agroclimatic information is of paramount importance for selecting appropriate crop varieties and adopting suitable agricultural practices, especially given the unpredictable nature of hybrid rainy seasons (Salack *et al* 2016). These crop-livestock-climate nexus experiments, conducted under ambient field conditions, provide an important proof-of-facts supporting the development of early warning systems, enabling

Table 1. Crop-livestock-climate intensification pathways for the Sahel.

Pathway	Scenario
Organic fertilizer + Agroclimatic Information	– 5 tons/ha of digestate from biodigester combined with intra-seasonal and seasonal agroclimatic information – 5 tons/ha of compost from the manual compost combined with intra-seasonal and seasonal agroclimatic information
Organic fertilizer + Microdose + Agroclimatic Information	– 5 tons/ha of digestate + 100 kg/ha (N-P-K) + Urea (100 kg ha^{-1}) combined with intra-seasonal and seasonal agroclimatic information – 5 tons of compost + 100 kg/ha (N-P-K) + Urea (100 kg ha^{-1}) combined with intra-seasonal and seasonal agroclimatic information

timely responses to potential agricultural crises. By actively monitoring climate indicators and receiving forecasts, farmers, pastoralists, and local authorities can proactively take preventive measures (Sanfo *et al* 2022). These measures may include adjusting planting date and grazing schedules, implementing drought- and flood-resistant strategies, and preparing for possible pest outbreaks (Daku *et al* 2022).

4.2. Soil amendments and crop yield improvements

One of the central findings of this study is the significant impact of organic amendments on soil nutrient levels and crop production. Similar observations have been reported by previous studies (Koulibaly *et al* 2009, Bationo & Buerkert 2001). These studies have emphasized the role of compost in enhancing soil conditions and nutrient supply, leading to improved crop yields. The present research expands upon this knowledge, demonstrating the benefits of both pit compost and digestate-based compost, particularly when combined with micro-doses of mineral fertilizers.

The integration of biodigester technology, composting, and micro-dosing practices offers short and medium-term benefits for enhancing soil vitality in the face of climate extremes. These climate-smart practices contribute to soil fertility improvement, enhanced water retention, increased resilience to climate-related challenges, and provide sustainable waste management solutions. Moreover, they can lead to significant cost savings and increased income for farmers. Notably, biodigester technology transcends mere agricultural fertilization by harnessing organic waste that would otherwise contribute to atmospheric greenhouse gas emissions. Instead, it valorizes this waste to produce gas and light in a dynamic and sustainable loop. The research by Wang *et al* (2023) and Srivastava *et al* (2025) are complemented by this study, highlighting the role of digestate-based compost in improving soil properties and nutrient availability. The findings from both studies underline the potential of organic amendments to not only enhance crop yields but also promote sustainable soil management practices, contributing to improving crop production and the long-term agricultural sustainability.

4.3. Intensification pathways and sustainability

The study identifies two intensification pathways that can increase crop productivity without adverse environmental impact. One involves the use of crop residues and composts, and the other incorporates crop residues, composts, and micro-doses of chemical fertilizers:

– Pathway 1: The use of crop residues and composts, both integrated into an agroclimatic information and advisory.

– Pathway 2: The incorporation of crop residues, composts, and micro-doses of inorganic fertilizers with an agroclimatic information and advisory.

Each of these pathways can be further divided into two sub-classes, as outlined in table 1. Importantly, both pathways are scalable and customizable to the local context of every farming system. They can be implemented on a larger scale within the Sahelian region, offering promising avenues for sustainable agricultural development and resilience-building in response to climate variability. These pathways also align with the broader sustainable agricultural intensification. Which aims to enhance productivity while ensuring environmental and climate cleaniness (Bationo & Buerkert 2001, Wang *et al* 2023).

4.4. Synergies and policy recommendations

Climate change is linked to acute, chronic, and transboundary multi-hazards, intensifying competition for land and resources between crop and livestock farming systems. Changing land use patterns exacerbate this competition, leading to nexus stressors such as land degradation, water scarcity, and potential conflicts between the two sectors. In the Sahel, relying solely on meteorological information is insufficient to improve crop productivity. Similarly, enhancing soil fertility alone does not necessarily translate into higher yields. Instead, a synergistic integration of both factors is essential for optimizing agricultural outcomes. In agropastoral systems, the incorporation of biodigester technology and composting practices presents a viable pathway to strengthening climate resilience in agriculture. These innovations contribute to improved soil fertility, enhanced water retention, and overall resilience of crops and livestock to climate extremes.

The pathways identified in this study offer practical solutions for smallholder farmers in the Sahel to improve soil fertility, crop yields, and overall agricultural sustainability under different weather situations. They can serve as a foundation for scaling up sustainable agricultural practices. Therefore, policymakers must promote integrated land-use planning to balance the needs of crop and livestock farming. This could involve zoning regulations that consider the suitability of land for each type of farming. For example, the creation of grazing areas and demarked transhumance corridors for livestock (Salack *et al* 2022) will reduce the competition and conflicts between farmers and herders on the seasonal pasture and water resouces in some resource-limited zones of the Sahel. To promote the widespread adoption of mixed farming systems that combine crops and livestock, climate-smart agro-advisory, the country-wide policies should include awareness campaigns, subsidies for the biodigester technology, and technical training to farmers.

5. Concluding remarks

In the Sahel tThe competition between crop and livestock farming systems is increasing as a result of in the semi-arid regions of the Volta and Niger River basins in West Africa has intensified due to an evolving land use patterns influenced by climate variability and change. To effectively address this challenge and promote sustainable intensification, we conducted integrated crop-livestock experiments spanning Burkina Faso, Ghana, Mali, and Niger under different weather conditions. . Our study suggested several intensification pathways that provide synergies of the two sectors to increase productivity while enhancing climate resilience in the semi-arid regions of the Volta and Niger River basins.

Our findings underscore the substantial impact of soil amendments, particularly organic fertilization using compost from pits and digestate-based compost from biodigesters, on soil nutrient levels, encompassing carbon, phosphorus, and nitrogen. These amendments compensate for plant nutrient exports,improved soil fertility, and increased crop production. The incorporation of micro-doses of chemical fertilizers alongside organic amendments resulted in substantial enhancements in crop yields, albeit with some variations across sites. However, the efficiency of these soil amendments is contingent upon the availability of timely meteorlogical information advisory. Hence, the introduction of a tailored agroclimatic information package, the AgInfo package, to empower farmers with critical weather forecasts and technical iteneraries and practice. This package equiped agro-pastoralists to make informed decisions regarding cropping systems, livestock management, and water resource allocation, crucial in the unpredictable climate of the Sahel.

The combination of biodigester technology, composting, and micro-dosing practices provided short and medium-term benefits, enhancing soil health, increasing water retention, and fortifying resilience to climate extremes. Furthermore, this sustainable approach contributed to waste management and greenhouse gas recycling, aligning with climate-smart agricultural practices. Ultimately, our study identified two primary intensification pathways that pave the way to sustainable agricultural development and climate resilience in the Sahel region. These pathways are based on the combination of crop residues, composts, and agroclimatic information and advisory system. Smallholder farmers, by embracing these practices, can improve their livelihoods, safeguard soil resources, and contribute to food security in the face of climate variability and change.

This study had two minor limitations. First, it encompassed a relatively short-term study period (i.e., 2018 to 2022), potentially limiting the considerartion of a large number of of long-term trends in the climate. Second, the reliability of the agroclimatic information (i.e., Weather forecasts) was crucial to ensure that the technical itineraries provided in the advisory system are effective. At some sites, the agroclimatic information exhibited weak skills in predicting on some extreme events (e.g., extreme dry spells). Further improvements of the forecasting skills will involve theuse of machine and deep learning algrothms.

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Conflict of interest

The authors have no conflict of interests that can influence the work reported in this paper.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Appendix

Methodes of sample analysis

Soil analysis. The analyses of were carried out on composite soil samples. For Sorghum, samples were taken at two depths: 0–20 cm and 20–40 cm. For maize, in addition to the depths 0–20 cm and 20–40 cm, an additional sampling was made at a depth of 40–150 cm to take into account the depth of cement of this crop. Sampling was carried out at five points, including a sampling point at each edge of the field and a point in the centre.

Sand, silt, and clay content of the soil sample were determined using the hydrometer method (densimetric) after chemically dispersing the soil sample with 10 ml of sodium hexametaphosphate ($Na_6(PO_3)_6$). The pH (pH water) was measured with an electronic pH meter in a suspension of distilled water at a 1:2.5 ratio (AFNOR, 1981). The total carbon content was determined following Walkley and Black (1934). For total nitrogen content, the sample was mineralized using the Kjeldahl method (Hillebrand *et al* 1953). The nitrogen content in the digestate was then determined using a distillation method. The available potassium was extracted using a 0.1 N hydrochloric acid (HCl) solution and a 0.4 N oxalic acid ($H_2C_2O_4$) solution. The available phosphorus was determined using the Bray I method (Bray and Kurtz 1945). This method involves extracting soluble phosphorus forms using hydrochloric acid in the presence of ammonium fluoride. The Potassium (K) content was measured using a flame photometer by comparing the intensity of radiation emitted by potassium atoms with that of standard solutions (20, 40, 60, 80 and 100 milli equivalent/L).

Analysis of compost samples. Both compost from the digestate and the compost from pit/surface were analyzed using the similar approaches. The parameters analyzed are similar to those analyzed in soil, except for phosphorus and potassium, which were measured as total content, and trace elements such as ammonium and nitrate. Total phosphorus in compost was determined using a mixed solution of ascorbic acid, ammonium molybdate, and potassium antimony oxytartrate. Molybdate ions react with phosphate ions to form a blue-colored complex, whose absorbance was measured at 720 nm. The intensity of the color is proportional to the phosphorus content. The measurement was done using an automatic colorimeter. Total potassium was determined using a flame photometer by comparing the intensity of radiation emitted by potassium atoms with standard solutions, directly after mineralization. Some trace elements extraction was carried out using a 1 N potassium chloride (KCl) solution with a soil-to-extraction solution ratio of 1:10. The Nitrate and ammonium were quantified from the extract by colorimetry using disulfophenic acid in an alkaline medium at 410 nm. Ammonium was also measured at 410 nm using a colorimeter with Nessler's reagent. The intensity of the complex's color is proportional to the ammonium content in the sample. However, the trace elements were not considered in the results of the this paper.

Initial physicochemical characteristics of soil and composts. Table A1 below presents the chemical characteristics of the digestates and compost on the two sites. There are higher levels of organic matter and carbon (in the range of 2 to 4%) compared to compost. On the other hand, the nitrogen content is slightly lower in digestates in compst compraison as can be expected in the case of weakly mineralized organic matter. As far as total P is concerned, there are 5 times more important consultations in digestates than in compost regardless of the site.

Table A1. Chemical characteristics of the compost and digestates used.

	Digestate dano	Compost dano	Digestate boassa	Compost boassa
Carbon and organic matter				
Total Organic Matter %	38.953	36.970	34.689	30.481
Total Carbon %	22.593	21.443	20.119	17.679
Total Nitrogen %	1.162	1.226	1.034	0.969
C/N	19	17	19	18
Phosphore				
Total Phosphorus (g/Kg)	11.55	2.57	13.09	2.31
Potassium				
Total Potassium (g/Kg)	4.48	5.37	4.92	3.59
Oligo elements				
Nitrate N-NO3 mg/Kg	15.04	5.60	18.04	5.04
Ammonium N-NH4 mg/Kg	14.28	5.42	12.66	7.66
Soil reaction				
pH water (P/V : 1/2.5)	6.84	6.76	7.02	6.31

Table A2. Initial physicochemical characteristics of the soil samples.

Site	Boassa		Dano		
Depth	0–20 cm	20–40 cm	0–20 cm	20–40 cm	40–150 cm
Soil Texture	L S*	L S	L S	LAS**	LAS
Total Clay %	13.73	17.65	17.65	21.57	29.41
Total Silt	9.80	13.72	9.80	9.80	17.65
Total Sand %	76.47	68.63	72.55	68.63	52.94
Carbon and Organic matter					
Total Organic Matter (CO) %	0.947	0.824	1.138	0.960	0.643
Total Carbon %	0.549	0.478	0.660	0.557	0.373
Total of Nitrogen %	0.056	0.050	0.050	0.045	0.033
Ratio C/N	10	10	13	12	11
Phosphor/Phosphorus					
Available phosphorus in ppm	6.14	5.51	5.30	4.61	3.86
Potassium					
Available potassium in ppm	99.36	71.13	67.74	94.84	91.46
Soil reaction					
pH Water (P/V : 1/2.5)	5.48	5.72	6.46	5.84	6.14

*LS: sandy loam; **LAS: sandy loam-clay

Whereas potassium is quite similar between the two sources of organic matter. The trace elements follow the same trend as the total P. While the pH is close to the temperature on both sides.

The physico-chemical characteristics of soils are based on soils with sandy loam texture on the surface of the two sites (table A2). While it became silty-clay-sandy from 20 cm in Dano, The carbon and nitrogen contents are low ($\leqslant$ 1%) and are characteristic of the ols in the region. The available Phosphorus and Potassoum are also low and are mainly located in the first 20 cm of soil. The pH is slightly acidic with higher acidity values in the soils of Boassa

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