**KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY, KUMASI, GHANA**

# CROPS-LIVESTOCK INTEGRATION AS A RESILIENCE STRATEGY TO CLIMATE CHANGE IN BURKINA FASO

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**in partial fulfilment of the requirements for the degree of**

**DOCTOR OF PHILOSOPHY**

**In**

**Climate Change and Land Use**

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## CERTIFICATION

I hereby declare that this submission is my own work towards the PhD degree in Climate Change and Land Use and that, to the best of my knowledge, it contains no material previously published by another person, nor material which has been accepted for the award of any other degree or diploma at Kwame Nkrumah University of Science and Technology, Kumasi or any educational institution, except where due acknowledgement has been made in the thesis.

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## DEDICATION

*This work is dedicated to God,*

*my father, Mr. Fatogoma Louis Pierre SANOU (of blessed memory),*

*my mother, Angèle SANOU,*

*my wife, Y. Jacqueline SANOU,*

*my sons and daughter, Alex T. Parfait, Aimé K. Christian, Ariel W. Steve, Anna Gloria, and my brothers Wenceslas (of blessed memory), Blaise, Jacques, Guy, Henri and Robert.*

# ABSTRACT

This study titled addressed a topical issue of climate change and its impacts on farmers' livelihoods and the role that an integrated crop-livestock system can play in building resilient farmers and agricultural systems. The research first of all analysed historical climate (rainfall, minimum and maximum temperature) trends across three climatic zones Sudan (Dano), Sudan-Sahel (Niou) and Sahel (Dori)) at annual, seasonal and decadal scales. Climates indices computation was done using the package ClimPACT2 GUI in R software. Annual and seasonal climate were compared using the independent t-test. Decadal climate indices were subjected to a Principal Component Analysis (PCA). The research also analysed the susceptibility or sensibility of crop production and livestock health to climate change. Thirdly, the research developed and/or updated measurement tool known as Crop-Livestock Integration (CLI) indicators for a holistic characterisation of integrated crop-livestock system. These indicators were developed based on the information from 589 farmers' households and secondary data. Above ground, data were collected from 4,733 trees over a total land area of 243.2 ha (80.1 ha, 78.8 ha and 84.3 ha in Sudan, Sudan-Sahel and Sahel zones, respectively). Due to the Sahel zone's insecurity, soil data could be collected only within Sudan and Sudan-Sahel zones. In total, 120 composite soil samples were collected for this purpose and 240 other samples for soil bulk density determination. Results revealed changes in climate conditions, more pronounced in temperature variations than in rainfall. In the Sudan-Sahel and Sahel zones, a re-wetting trends was observed over the last decade supporting the re-greening hypothesis of the Sahel. Despite some positive effects of the climate indices, crop failure was the major impact of climate pejoration across zones. Similarly, livestock health was majorly negatively affected by climate deterioration though the resurgence of diseases due to climate change. Climate indices could explain 23.0 - 50.2 % of the variations in crop yield and an increased cases of livestock diseases occurrence by 1-9.4 units due to the deterioration in climate conditions across climatic zones. Changes in climatic conditions may also induce microbial proliferation and host susceptibility to result in the emergence, redistribution, and changes in the incidence and intensity of pest infestations. The study concluded that crop-livestock integration is underperforming in Burkina Faso and can be improved. Majority farmers (91.6 %) in the Sudan-Sahel zone are practising full crop-livestock integration, unlike the Sahel (62.3%) and Sudan (48.2%) zones. However, only 14.8%, 10.5% and 5.1 % showed the effectiveness of integration in the Sudan-Sahel, Sahel and Sudan zones, respectively. CLI was comparatively more effective in Sudan-Sahel (65.9±32.0 %) than Sahel (44.9±29.5 %) and Sudan zones (35.6±35.0 %). Integration indicators were significantly associated with farm emissions, productivity, biodiversity and soils nutrients. CLI is also a tree-based system with high sequestration potential that could significantly counterbalance the whole system emissions. However, the coverage of fodder needs is negatively associated with soils nutrients content indicating field nutrient mining if an appropriate scheme of nutrient return to the soils as manure is not set. An adequate combination of CLI components offers an opportunity to build resilient farming systems in Burkina Faso to adapt to the changing climate.

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## LIST OF ABBREVIATIONS AND ACRONYMS

AFOLU: Agriculture forestry and other land use and land cover

AGB: Aboveground biomass

BGB: Belowground biomass

CFN: Cropping financial needs referring to the annual required expenditures for cropping

CLI: Crop-livestock integration

$CO_2$: Carbon dioxide

CoCFN: Coverage of crop financial needs

CoDPN: Coverage of draft-power needs

CoFN: Coverage of financial integration nneeds

CoFN: Coverage of fodder needs

CoLFN: Coverage of livestock financial needs

CoMN: Coverage of manure needs

CWP: Crop Water Productivity

DBH: Diameter at Breast Height

DIE: Daily Integration Effort

DJF: Season December-January-February

FAO: Food and Agriculture Organization of United Nations

FinCLI: Financial integration

FRC: Financial resource from cropping redirected by the household to support livestock breeding expenditures

FRL: Financial resource from livestock redirected by the household to support cropping expenditures

GHG: Greenhouses gases

GHGs: Green House Gases

GPS: Global Positioning System

GWP: Global warming potential

IE: Integration Effectiveness

IEffi: Integration efficiency

INDC: Intended Nationally Determined Contribution

INERA : Institut de l'Environnement et de Recherches Agricoles

IPCC: Intergovernmental Panel on Climate Change

JJA: Season June-July-August

LFN: Livestock financial needs referring to the annual required expenditures for livestock feeding and veterinary costs

LI: Level of Integration

Libio: Level of bio-physical integration

LULC: Land Use Land Cover

LULC: Land Use Land Cover

LWP: Livestock Water Productivity

MAM: Season March-April-May

MIE: Monthly Integration Effort

MMS: Manure management systems

NFF: Number of financial fluxes

SON: September-October-November

$TCO_{2e}$: carbon dioxide equivalent

TIE: Total Integration Effort

Tmax: Maximum temperature

Tmn: Minimum temperature

Total water productivity (TWP)

UNFCCC: United Nation Framework Convention on Climate Change

W: Workers

WASCAL: West African Science Service Center on Climate Change and Land Use

WD: Working days.

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All my gratitude goes to the farmers across the study areas. I appreciate their contribution and cooperation during data collection and hope that the findings of this work will support informed decision-making both at the farm level and the policy making level in Burkina Faso.

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# CHAPTER 1: INTRODUCTION

## 1.1 Background to the Study

The world's population estimated at 7.7 billion in mid-2019 continues to grow and is expected to reach 8.5 billion in 2030, 9.7 billion in 2050 and 10.9 billion in 2100 (United Nations, 2019). Likewise, Sub-Saharan Africa (SSA) population, estimated at 1.1 billion, is expected to grow and reach 1.4 billion in 2030, 2.1 billion in 2050 and 3.8 billion in 2100. Ensuring food security to growing sub-Saharan Africa populations needs considerable increases in food production (Bremner, 2012). Meeting the needs of the present and future population is likely to remain challenging, because of the low production performance in agricultural sectors (livestock and crops). Countries in SSA are producing under their actual agricultural potential (Henderson et al., 2016; Pradhan et al., 2015). The related consequences of yield gap will be the inability of production systems to cover growing population's current and future food needs. For instance, SSA has the biggest gap between cereal consumption and production, among all the continents with a likelihood that this situation will worsen by 2050 where cereals demand is expected to triple (Ittersum et al., 2016). Changes in climate conditions highly contribute to this worsening situation leading to more vulnerability of farmers (income reduction, increase in famine and poverty). Building their resilience could be done through climate-smart initiatives, including a crops-livestock integration system. Existing research has focused on sustainable intensification of productivity (Ghahramani et al., 2020) and ecological intensification of the mixed crop-livestock farming (Sulc and Franzluebbers, 2013). Others were on energy efficiency (Bénagabou et al., 2013), stability of soils fertility (Blanchard et al., 2014) and trade-offs of crop residue (Andrieu et al., 2015) in an integrated crop-livestock system. Generally, substantial research work has been done on nutrient flows, soil quality, crop performance, and animal weight gain in commercial crop-livestock integration system (CLIS). There is insufficient knowledge on greenhouse gas (GHG) mitigation, drought and heat tolerance in the system (Garrett et al., 2017), indicators of the system functioning (Bénagabou et al., 2013) and its water productivity. In Burkina Faso, some relevant studies have been carried out on crop-livestock integration and its implications for food security, socio-economic and environmental performances. Henderson et al. (2018) studied the economic potential of crop residues management in mixed farming systems in Burkina Faso in a context of climate change and found that residues retention causes trade-offs between crop and livestock production. However, fertilisation can raise returns to both activities. In addition, CLI was found to improve both economic and ecological intensification (Vall et al., 2011; Vall et al., 2006); and reduces the risks of exposure to climatic hazards and economic uncertainties (Vall et al., 2011). Furthermore, farm with a high level of the crop-livestock association presented the best sustainability indicators, including technico-economic, environmental and food security (Vall et al., 2017). Moreover, Crop-livestock integration positively impacts energy efficiency and lessens fossil fuel use in traditional farms (Jin et al., 2021). Animal energy for traction lessens machinery utilization and thereby the uses of non renewable sources of energy (mainly fossil fuel). In the same way, crop residues and organic fertilizer reduce the utilization of concentrate feed and chemical fertilizer, respectively (Benagabou, 2018; Adler et al., 2015). Furthermore, the integrated crop-livestock system improves recycling, autonomy and energy efficiency of the farming system (Bénagabou et al., 2017). Taking advantage of CLI's full complement of crop and livestock components also results in a strong climate adaptation strategy (Rigolot, Voil, et al., 2017). Indeed, CLI contributes to the diversification of revenues sources, reduces risk of exposure to climatic hazards and economic uncertainties. Moreover, the integrated system improves energy availability and soil organic carbon (Vall et al., 2011) through the availability of crop residues. Despite all its advantages, CLI is facing number of challenges including workforce labour demand by shortage for the composting process, strong adoption of preference for conventional agriculture agricultural practices and trade-offs in the use of crop residues within the system..

Up-to-date information is needed on the integrated crops-livestock system and its interrelationship with carbon sequestration, GHG emissions, and soil fertility. The updated information regarding this innovative practice could support informed decisions in building resilient and sustainable farming system in Burkina Faso.

According to Shiferaw et al. (2014) the recurring nature of climate-induced disasters and their adverse impacts on basic human well-being necessitates seeking sustainable alternatives that enhance climate resilience. The current research work was undertaken to add to the state of knowledge on crop-livestock integration particularly within Burkina Faso. To the existing indicators developed by Bénagabou et al. (2013) new set of indicators (integration effectiveness, integration efficiency, nature of integration (passive or active), financial integration) can be added to allow a better characterisation of the reality of crop-livestock integration. Moreover, there is a need to deepen the state of knowledge on CLI as contributing to the improvement of sustainable production, reduction of greenhouse gases emissio4, improvement of soil characteristics, improvement of water productivity and carbon sequestration at the farm level. Also it is important to investigate the optimum combination of crop and livestock components suitable for a sustainable farming system in the Sudan, Sudan-Sahel and Sahel agro-ecologies zones of Burkina Faso.

The reasonable hypothesis of this research work is ***"an optimal interaction between crop and livestock within an integrated crop-livestock system is possible in Burkina Faso to ensure sustainable agriculture in the context of climate change".***

## 1.2 Statement of the Problem and Justification for the study

The altered climate conditions in West Africa, including Burkina Faso, have induced regional average yield declines of 10-20 % for millet and 5-15 % for sorghum (Sultan et al., 2019). This situation is likely to worsen as future projected temperature is expected to increase and rainfall decline (PANA Burkina, 2007); with a plausible future increase in farmers' vulnerability if judicious and urgent measures are not taken to stem this trend.

Agricultural land demand increases accordingly, explaining the majority of changes in land use and cover (LUC) (Blein et al., 2008) in recent times. For these authors, the increase in food production mostly depends on cropland areas expansion (229 %) rather than the increase in crop yields (42 %). When crop yields decrease due to soil fertility decline, farmers increase the cultivated area where available, to compensate for the loss of production. Land-use and Land Cover change (LULCC) and climate change form a vicious circle. Indeed, LULCC through cropland expansion, exacerbates climate change.

The loss of vegetation due to LULCC increases the amount of carbon dioxide released into the atmosphere due to sink reduction and increased release from carbon sources (vegetation, soils etc.). In turn, the increased release of carbon dioxide into the atmosphere contributes to global warming and to climate change.

This vicious circle might be fueled by an increase in human population and herd size, leading to further pressure on natural resources through more demand for crop and grazing lands, with their direct or indirect impacts on greenhouse gas emissions. Appropriate reduction of yields gaps can contribute to climate mitigation and farmers' resilience building. However, this is far from being achieved within SSA' agro-systems, including Burkina Faso. This to some extent, can be explained by the fact that these agro-systems are globally dominated by mono systems of crop and livestock farming which are highly sensitive to climate deterioration (Hassan, 2010). Indeed, the decoupled livestock and cropland systems induces a substantial reduction of manure recycling rate and has have a detrimental effect on the environment (Jin et al., 2021). Rebuilding the links between livestock and croplands, at the expense of mono-systems, is one of the vital pathways to the sustainability of agricultural systems (Jin et al., 2021).

The high sensitivity of agro-systems to climate change, further accentuates farmers' exposure to climate vulnerability. The issue of adequate response to farmers' vulnerability that contributes to building their resilience to face climate change, constitutes the current research problem. Precisely, this research is interested in the role that crop-livestock integration (CLI) plays as a resilience strategy to climate change in Burkina Faso. To this end, an investigation was conducted to assess the influence of CLI systems on farm productivity, soil properties, greenhouse gas emissions and carbon stock within the mixed-crop-livestock farming system.

### 1.3 Research Questions

1. What has been the climate trend in the three climatic zones of Burkina Faso from 1961 to 2020?
2. How does climate evolution influence agro-pastoral productions across the climatic zones of Burkina Faso?
3. How does crop-livestock integration perform across the three climatic zones of Burkina Faso?
4. How do integrated crops-livestock systems influence farm water productivity, carbon stock and greenhouse emission?

### 1.4 Hypotheses

1. The three climatic zones of Burkina Faso have experienced significant changes in temperature and rainfall patterns from 1961 to 2020.
2. Changes in climate patterns across the climatic zones of Burkina Faso have positively influenced agro-pastoral productions.
3. Crop-livestock integration performance varies across the three climatic zones of Burkina Faso, potentially due to the distinct climate conditions of each zone.
4. Integrated crops-livestock systems can potentially enhance farm water productivity, increase carbon stock, and reduce greenhouse gas emissions.

## 1.5 Objectives of the Study

The aim of the study was to assess the role of crop-livestock integration as a resilience strategy to climate change in Burkina Faso.

Specifically, the study sought to :

1. Analyse climate change and variability across three climatic zones of Burkina Faso from 1961 to 2020.

2. Determine the influence of climate change and variability on agro-pastoral production across the three climatic zones.

3. Evaluate the performance of crop-livestock integration across the three climatic zones of Burkina Faso.

4. Assess the influence of the integrated crop-livestock system on water productivity, carbon stock and greenhouse gases emission across the three climatic zones.

## 1.6 Significance of the Study

The current study is important to academia because it will add new scientific information to the existing knowledge on the integrated crop-livestock system. The current study's findings will provide information to policy makers for informed decision making in the perspective of farmers' resilience building in a region prone to numerous challenges. Policy makers could popularize the optimal combination of crop and livestock components to give more incentives to farmers in Burkina Faso.

## 1.7 Organization of the Chapters

**Chapter 1** presents the general introduction including the problem statement, the objectives and the related research questions and the significance of the study.

**Chapter 2** provides a literature review on the concepts related to climate change, its drivers, its impacts/adaptation; carbon sequestration; water productivity, crop-livestock integration. It also addresses existing knowledge on crop-livestock integration, research gaps and the significance of addressing them. **Chapter 3** addresses specific objective 1 in analysing climate patterns over the last sixty years within the study sites across the three climatic zones of Burkina Faso. **Chapter 4** addresses objective 2 determining the influence of climate change on agro-pastoral activities within the study sites across these climatic zones. **Chapter 5** concerns objective 3. In this Chapter, it will be question of developing/updating integration indicators and of the holistic characterisation of crop-livestock integration across zones. **Chapter 6** focuses on the analysis of how greenhouse emission, carbon stock and farm productivity are influenced by the integrated crop-livestock system in the country. This chapter also look at the best combination of crop and livestock modules for a sustainable farming system in Burkina Faso. **Chapter 7** presents the study's conclusions, limitations and relevant recommendations.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Definitions of Key Concepts

### 2.1.1 Climate change

Climate change consists in a change in the state of the climate over time (IPCC, 2007a) identifiable by the mean of statistical tests (IPCC, 2018). This change refers to persistent changes in the mean and/or the variability of its properties over an extended period, typically decades or longer. The causes of climate change may be natural or anthropogenic changes in the composition of the atmosphere or in land use IPCC, 2018). According to the *United Nations Framework Convention on Climate Change (UNFCCC)*, climate change refers to a change of climate attributed directly or indirectly to mankind's activity that alters the global atmospheric composition and that is in addition to natural climate variability observed over comparable time periods (IPCC, 2018). The *UNFCCC* thus distinguishes between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes (IPCC, 2007a).

### 2.1.2 Extreme weather event

An extreme weather event is an event that rarely occurs at a particular place and time of the year. This may vary from place to place in an absolute sense and is not obviously attributed to anthropogenic climate change because it might have occurred naturally (IPCC, 2007b). However, in the case of the persistence of extreme weather for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme. Drought or heavy rainfall are examples of extreme climate events (IPCC, 2007b).

### 2.1.3 Climate change mitigation

Climate change mitigation consists of reducing and enhancing the sinks of greenhouse gases (GHGs) through human intervention (IPCC, 2014b). Climate mitigation can also be done through actions contributing to reduce the sources of other substances (particulate matter; carbon monoxide, nitrogen oxides ($NO_x$), Volatile Organic Compounds and other pollutants) which may contribute directly or indirectly to limiting climate change (IPCC, 2014b). These small particles can considerably affect the composition of tropospheric ozone ($O_3$) with an indirect effect on the climate (IPCC, 2014b).

### 2.1.4 Adaptation to climate change

Adaptation consists of a process of adjustment to actual or expected climate and its effects. Adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects IPCC, 2014a).

### 2.1.5 Resilience

Resilience refers to the capacity of social, economic, and environmental systems to cope with a hazardous event or trend, or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure while also maintaining the capacity for adaptation, learning, and transformation (IPCC, 2014a; IPCC, 2018).

### 2.1.6 Carbon sequestration

Carbon sequestration is a natural or artificial process by which carbon dioxide is removed from the atmosphere and held in solid or liquid form. It consists of removing carbon from the atmosphere and depositing it in a reservoir (IPCC, 2018). IPCC (2014b) described sequestration as the uptake of carbon-containing substances, particularly carbon dioxide ($CO_2$), in terrestrial or marine reservoirs. Biological sequestration is a natural one involving a direct removal of $CO_2$ from the atmosphere through land-use change (LUC), afforestation, reforestation, re-vegetation, carbon storage in landfills, and practices that enhance soil carbon in agriculture (cropland management, grazing land management) (IPCC, 2014b). Whereas, physical sequestration includes separation and disposal of carbon dioxide from flue gases (for use in the food industry) or from processing fossil fuels to produce hydrogen ($H_2$) and carbon dioxide-rich fractions and long-term storage underground in depleted oil and gas reservoirs, coal seams, and saline aquifers (IPCC, 2001a).

### 2.1.7 Greenhouse gases and global warming

Greenhouse gases (GHGs) consist of gaseous constituents, both from natural and anthropogenic sources, which absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, by the atmosphere and by clouds (IPCC, 2018; IPCC, 2007b). This property of absorbing and emitting radiation contributes to the greenhouse effect. The main greenhouse gases are water vapour ($H_2O$), carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), methane ($CH_4$), and ozone ($O_3$). Besides these gases, there are entirely man-made greenhouse gases such as halo-carbons and other chlorine and bromine-containing substances dealt with under Montreal Protocol. Furthermore, other greenhouse gases were indicated under the Kyoto Protocol. These gases consist of Sulfur hexafluoride ($SF_6$), Hydrofluorocarbons (HFCs), and Per-fluorocarbons (PFCs) (IPCC, 2018; IPCC, 2007b).

Global warming refers to the estimated increase in global mean surface temperature (GMST) averaged over 30 years, or the 30 years centred on a particular year or decade, expressed relative to *pre-industrial* levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue (IPCC, 2018).

### 2.1.8 Carbon dioxide equivalent emission

Carbon dioxide equivalent ($CO_{2e}$) consist of the quantity of carbon dioxide ($CO_2$) emission that would cause the same integrated radiative forcing or temperature change, over a given time horizon, as an emitted amount of a particular greenhouse gas (GHG) or a mixture of GHGs (IPCC, 2018). The computation and choice of equivalent emissions and the appropriate time horizons can be made in several ways. Most typically, the $CO_2$-equivalent emission is obtained by multiplying the emission of a GHG by its global warming potential (GWP). The GWP index determines the relative contribution of gas to the greenhouse effect. It is defined as the cumulative radiative forcing between the present and a selected time in the future caused by a unit mass of gas emitted now (IPCC, 1996). The GWP (with a period of 100 years) of $CO_2$, $CH_4$ and $N_2O$ is 1, 21 and 310, respectively, that of $CO_2$, $CH_4$ and $N_2O$ is 1, 56 and 280, respectively considering a period of 20 years (used in the current study).

In the case of mix of GHGs the $CO_2$-equivalent is obtained by summing the $CO_2$-equivalent emissions of each gas. $CO_2$-equivalent emission is a common scale that allows the comparison of emissions from different GHGs (IPCC, 2018).

### 2.1.9 Emission factor

An emission factor is a coefficient that quantifies the emissions or removals of a gas per unit activity. Emission factors are often based on a sample of measurement data, averaged to develop a representative emission rate for a given activity level under a given set of operating conditions (IPCC, 2019).

### 2.1.10 Crop-livestock integration

Crop-livestock integration (CLI) consists of a set of agricultural practices that relate agriculture component to livestock module within a mixed crop-livestock system or a non-specialized territory (Benagabou, 2018). CLI was initially introduced in Sub-Saharan Africa in the 1950s to promote the use of animal energy through animal traction to improve land and labour productivity (Benagabou, 2018).

Currently, the CLI system offers, beyond productivity, an opportunity to effectively contribute to greater farm efficiency and much more to the sustainability of the agricultural systems (Thornton and Herrero, 2015). Indeed, this system provides double advantages of activities diversification and integration. Diversity of farming activities may increase income stability and reduce risks to resource-poor households, while integration using the outputs of one activity as inputs of another activity, may reduce dependency on external resources (Rufino et al., 2009). Furthermore, the CLI system is a springboard to support ecological processes such as recycling (Bonaudo et al., 2014; Stark et al., 2016). CLI system also has the advantage of reducing fossil energy utilisation (Gerber et al., 2013; Vigne et al., 2013), thereby contributing to the mitigation of GHGs and definitely to the reduction of global warming and climate change. CLI can be done at two scales (farm level and that of the territory) (Dugué, 2013) or more (global, regional, landscape and farm-scale) (Herrero et al., 2010) or even at a smaller scale (i.e plot). This offers multiple possibilities of material exchanges between components and the environment at different territorial scales (Figure 2.1). Crop-livestock integration is characterized by three main pillars: animal traction, organic manure and crop residues (Landais and Lhoste, 1990). Indeed, in a well integrated system, livestock provides draft power for land cultivation and manure for soil fertilisation, while crop residues constitute key feed resources for livestock (Figure 2.1) (Herrero et al., 2010). The synergies between cropping and livestock rearing offer various opportunities to improve productivity and resource use efficiency, thereby ensuring food security and household income (Thornton and Herrero, 2015).

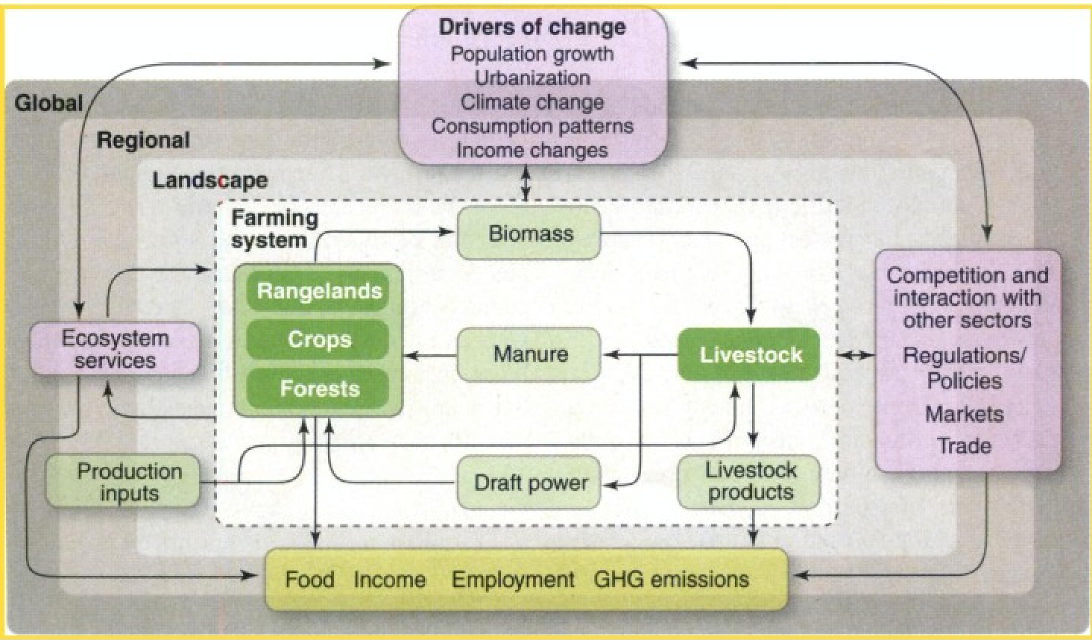


Figure 2.1: Main interactions in mixed crop-livestock systems in the developing world. Source: Herrero et al. (2010).

The integrated crop-livestock system offers potentialities of both carbon sequestration and emissions with balance depending on the nature and the level of integration of the components involved. According to Ortiz-Gonzalo et al.(2017); the GHG exchange between the biosphere and the atmosphere in such a system is driven by five processes involving C-N fluxes between farm components (Figure 2.2). The first process consists of livestock feeding on a mixture of fodder, crop and weed residues, and off-farm concentrates (additional N source imported to the farm). Feed digestion is accompanied by cellulose break down in the rumen where methanogenesis take up the resulting hydrogen and release methane ($CH_4$) during the enteric fermentation process (Tongwane and Moeletsi, 2021; Johnson and Ward, 1996).

The second process consists of a mixture of animal excreta (urine and dung) with feed refusals and bedding materials, serving as input to the manure management system (MMS). This management system has an influence on both methane ($CH_4$) and nitrous oxide ($N_2O$) emissions (Ortiz-Gonzalo et al., 2017). $N_2O$ is directly emitted from a nitrification and denitrification processes and indirectly through ammonia ($NH_3$) volatilisation, deposition and nitrate ($NO_3$) leaching (Amon et al., 2006). The third process in the system involves inorganic and organic soils fertilisation with background emissions (Oenema et al., 2005). Additionally, carbon dioxide ($CO_2$) is emitted from soils respiration processes and the breakdown of organic matter (Janzen, 2004). The fourth process involves the turnover of manure and biomass residues and plant root exudates to ensure organic carbon accumulation into the soil (Lal, 2004).

The fifth process consists in the bio-sequestration of C in above and belowground plant structures during plant growths within the agroforestry systems (Mutuo et al., 2005).

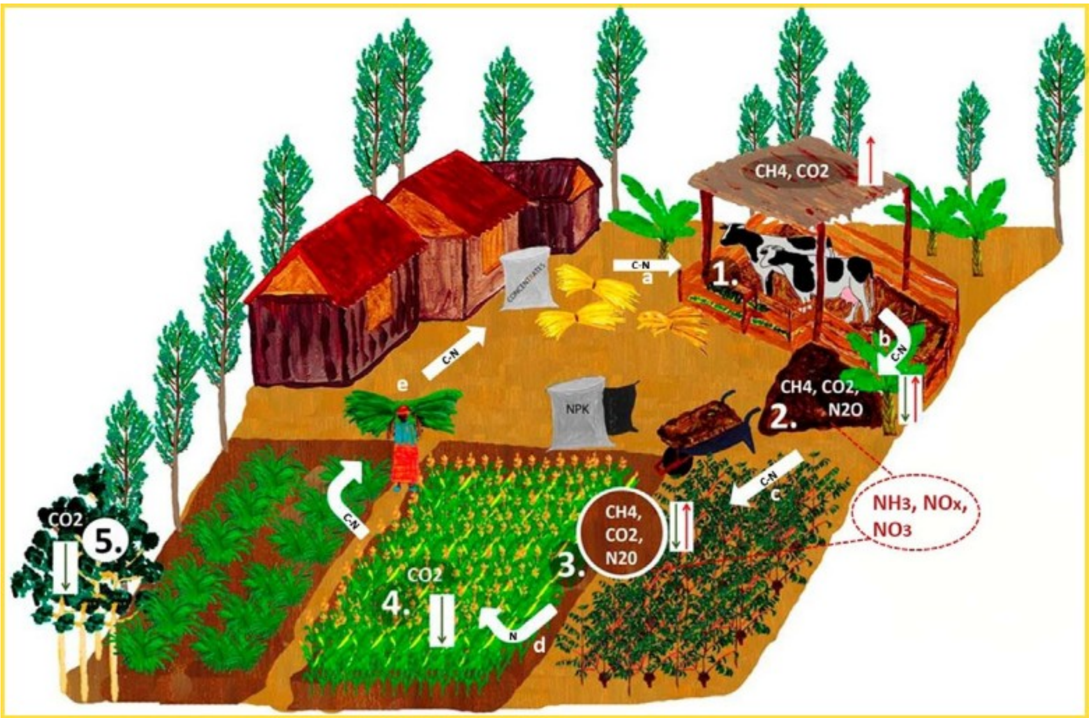


Figure 2.2: Farm-scale livelihood activities, greenhouse gases emissions (GHG) and carbon (C) sequestration in integrated smallholder crop-livestock system. The numbers (1–5) represent farm components: (1) livestock, (2) manure management systems (MMS), (3) soil, (4) crops and (5) trees. The letters (a–e) are associated with fluxes of C and N: (a) fodder, crop residues and concentrates, (b) dung, urine and bedding materials, (c) inorganic fertilizer, manure and crop residues, (d) nitrogen uptake by crops, (e) the biomass harvested that can follow different pathways: livestock feed, compost heap or mulch. Source: Ortiz-Gonzalo et al. (2017)

### 2.1.11 Water productivity

Productivity is generally defined as ‘the ratio of valuable unit output to input (Kijne et al., 2003), i.e. the efficiency and effectiveness with which resources, personnel, machines, materials, facilities, capital, time are utilised to produce a valuable output (Gebreselassie et al., 2009). Therefore, water productivity refers to the ratio of valuable output to a certain amount water used or depleted during the production of that output. Indeed, it measures the ability of an agricultural system to convert water into food (Descheemaeker et al., 2013). In other words, water productivity consists of the benefits derived from water use. Therefore, the numerator has a physical or economic term expressing the benefit and the denominator expressing the volume (Molden et al., 2007) or the value of water depleted (Haileslassie et al., 2009). Moreover, in a large sense, water productivity objectives are to produce more food and improve the associated income, livelihood and ecological benefits, at a lower social and environmental cost per unit of water depleted (Molden et al., 2007). These authors also describe water productivity in terms of physical and economic water productivity. Physical water productivity is defined as the ratio of the mass of agricultural output to the amount of water used, and economic productivity is defined as the value derived per unit of water used. Furthermore, water productivity can also be measured specifically for crops (crop water productivity) and livestock (livestock water productivity), based on the same principles of water accounting (Peden et al., 2007); i.e., as the ratio of gross livestock and crop returns to total Evapotranspiration (ET) water in producing livestock feeds and crops. The denominator in LWP computation may include degraded water and downstream discharge accounted as depleted water because of the impossibility or the related cost to purify and recapture lost water for reuse (Peden et al., 2007).

**Crop water productivity (CWP):** is defined as the amount or value of crop product with the amount of water depleted or diverted during the production processes (Kijne et al., 2003).

**Livestock water productivity (LWP):** consists of the ratio of livestock's beneficial outputs and services to water depleted in their production, known as evapotranspiration (ET) associated with feed production (Haileslassie et al., 2009). This concept was first defined by Peden et al. (2007) and can also include water depleted in slaughterhouses and milk processing facilities. Peden et al. (2007), in the estimation of LWP, suggest that the value of manure should be included among the benefits attributed to animal water production, because a part of the transpired water is used to produce indigestible feed (30-80 % of feed consumed). Indeed, indigestible feeds end up as manure which contribute to the fertility replenishment of soil, household fuel, and construction material for homes. The methodology in LWP estimation for the current study will follow the suggestion of these authors.

## 2.2 Overview of climate change in Sub-Saharan Africa

Like the rest of the world, in Sub-Saharan Africa (SSA), Climate Change is a real phenomenon. It is likely to worsen in the future (IPCC, 2007b) even if the magnitude and the nature of its impacts on temperature and rainfall distribution patterns remain unclear (Cooper et al., 2008). Communities in this region rely mainly on rain-fed agriculture and pastoralism for their livelihoods. This situation makes them vulnerable to climate hazards. Indeed, these communities are already struggling to cope effectively with the impacts of the current climate variability and will be more susceptible to future climate change. According to these authors, by 2025, cereal deficit will account for about 35 million tons characterising SSA as a “food trade hotspot”. In the region, the existing rainfall variability and the increase in the frequency of climate extremes are likely to be exacerbated as a consequence of inevitable global warming (Ly et al., 2013; Salack et al., 2015; Sarr et al., 2015; Sylla et al., 2016; Wedajo et al., 2019; Worku et al., 2022) and its associated changes in climatic patterns (IPCC, 2007b). Face with the impacts of climate change in Sub-Saharan Africa (Abubakar et al., 2020), there is a need to develop new options and innovations to enhance the resilience of agricultural productivity and reduce the vulnerability to shocks in this region. This is possible in SSA with appropriate investment in farming practices of rural communities (Cooper et al., 2008).

## 2.3 Climate change and adaptation in Burkina Faso

### 2.3.1 Climate change in Burkina Faso

Burkina Faso in Sub-Saharan Africa is facing changes in climate characteristics (Ibrahim et al., 2014). For instance, since 1970, the rainfall regime has experienced high variability and a decrease in rainfall amount countrywide (Ibrahim et al., 2014). Furthermore, according to (Alvar-Beltrán et al. (2020), climate change in Burkina Faso is characterised by a shift in the onset and cessation of the rainy season, an increase in rainfall variability and dry-spell duration, heavier precipitations and increasing temperature. This situation has serious implications including changes in soil moisture, soil quality, crop resilience, timing/length of growing seasons, agro-pastoral productions (Zampaligré et al., 2014; Kima et al., 2015; Waongo et al., 2015), atmospheric temperatures, weed insurgence, flooding, unprecedented droughts, rise in sea level and much more (Ozor and Cynthia, 2011). Moreover, climate change and variability have over the past decades been affecting the livelihoods of agriculturalists and pastoralists throughout the three agroclimatic zones countrywide. Indeed, it is reported that there is a decrease in forage availability, livestock fertility, and meat and milk yields (Alvar-Beltrán et al., 2020). The knowledge of the incidences of climate change and much more of those expected in future is essential for building an adequate and sustainable resilience of farmers' communities. Nevertheless, there are uncertainties in the future climate patterns in Burkina Faso. Indeed, results obtained from regional (RCM) and global (GCM) climate models and following the Representative Concentration Pathways (RCPs) 4.5, 8.5 and A1B scenarios, indicated high discordances in the future climate patterns (Op de Hipt et al., 2018; Ibrahim et al., 2014). Despite the uncertainties in the projection of the future climate patterns in West Africa and within Burkina Faso in particular, projections have proved some important changes in rainfall characteristics countrywide. Indeed, it is expected a decrease of 3 % in low rainfall events (0.1 – 5mm/d); an increase of 15 % in high rainfall events (>50mm/d), a delay in rainy season onset and a lengthening of dry spells by 20 % (Ibrahim et al., 2014). Furthermore, by 2045, due to the future climate change, it is projected a profit reduction of smallholder farmers up to 15 % of the baseline farm profit within northern Burkina Faso (Henderson et al., 2018).

### 2.3.2 Adaptation to climate change in Burkina Faso

In Burkina Faso, numerous adaptation strategies have been developed to reduce the vulnerability of the agricultural sector. Nevertheless, the adoption of these strategies remains challenging. Likewise, all new technology or innovation is influenced by several factors, including the educational level, the compatibility of the strategies with the social values and norms, the complexity of their implementation, and the possibilities to test and observe their performances (Rogers, 1995). Moreover, Thiombiano & Nana (2018), found that climate change adaptation strategies is influenced by access to climatic information, being a member of a group of producers, and possession of land pits.

Of the number of adaptation strategies in Burkina Faso, Zampaligré et al. (2014), reported numerous adaptation strategies adopted by agro-pastoralists and pastoralists. Indeed, for these authors, agro-pastoralists adapt their activities to climate change through crop diversification, crops-livestock association/integration, water harvesting technologies, and soil conservation measures such as stone bunds and half-moons. Pastoralists' adoption strategies consist of cereal cropping, and seasonal, annual, and permanent migration. Strategies adopted by agro-pastoralists and pastoralists are influenced by agro-ecological zones, cultivated area, ruminant herd size and level of education. Alvar-Beltrán et al. (2020), pointed out that adaptation strategies differ between Sahel and Sudan zones. In the Sahel, adaptation strategies rely more on traditional knowledge and experimental approaches, while market-oriented in the Sudan zone. Indeed, these strategies are implemented in climatic, social and economic contexts. For the same authors, the most widespread adaptation practices are related to soil and water conservation technologies that act in reducing soil erosion and enhance infiltration. With increasing rate of change and intensification of natural hazards, these practices might be insufficient in the long term. In this context, decision makers in Burkina Faso should develop a road map to improve agrometeorological services including challenges, goals and benefits of providing end users with agrometeorological information for tactical farming decision making. Indeed, actions to counteract climate change impacts should evolve and build farmers' livelihood strategies to sustain their resilience in the context of global change. In this perspective, alternatives and sustainable strategies should be investigated for farmers to adapt to a changing climate.

## 2.4 Developments in crop-livestock integration

Mixed farming system such as crop-livestock integration or crop-livestock-forest systems are strategies for reducing both direct emissions and emissions from deforestation by increasing land productivity and diversifying productions (Lemaire et al., 2013b; Herrero et al., 2010a).

Historically, the promotion of mixed farming in Africa followed perceptions relative to : (i) the low provision of adequate levels of nutrition for a growing population; (ii) the responsibility of previous bad agricultural practices in the destruction of the environment; (iii) the incompatibility with higher levels of socio-economic development (Sumberg, 1998). For these authors, bad practices culminated in shifting cultivation and nomadic pastoralism. Therefore, mixed farming was presented as an alternative, expected to produce more and to be more efficient than shifting cultivation. Indeed, mixed farming as indicated by Hall (1936), allows producing the same amount of food from smaller area of land continuously cropped. This high productivity and efficiency of mixed farming was intended to reduce the pressure on the remaining forest resources (Sumberg, 1998). On another side, mixed farming systems constitute the backbone of African agriculture and provide the majority of the staples consumed by millions of poor people in Africa: between 41 and 86 % of the maize, rice, sorghum and millet, and 90 % of the milk and 80 % of the meat (Thornton & Herrero, 2015; Herrero et al., 2010).

### 2.4.1 Integrated crop-livestock systems in Burkina Faso

#### 2.4.1.1 Crop-livestock integration, energy efficiency and food security

Henderson et al., (2018) conducted a study within northern Burkina Faso on the economic potential of residue management and fertilizer use to address climate change impacts on mixed smallholder farmers. These authors used the Positive Mathematical Programming (PMP) model to assess the ex-ante potential of residue retention and fertilisation to address challenges relative to yield gaps in the mixed smallholder farming system. They found that residues retention causes trade-offs between crop and livestock production, while fertilisation can synergistically raise returns to both activities. They reported combined N fertilization and residue retention to be globally, the most profitable, followed by the fertilizer alone. The authors proposed further research into : (i) co-benefits related to soil health and soil carbon sequestration; (ii) carbon and other ecosystems services payment that can increase the viability of some sound agricultural practices and allow more profitability for smallholder farmers.

Bénagabou et al. (2017), conducted a research in the west of Burkina Faso on crop-livestock integration. The objective of the study was to analyse the effect of integration practices on the autonomy, recycling and energy efficiency of farming households. Using the Ecological Network Analysis (ENA), the authors key findings were: (i) crop-livestock integration practices such as residue storage and organic fertilizer production per unit livestock improve recycling, autonomy and energy efficiency of the farming system; (ii) the level of crop-livestock integration is not optimal and can be improved. This was because of the insufficient manpower, the limited transport capacity, the inability to collect waste from mobile livestock, the limited cultivated area to cover livestock needs from cropped pasture. In a nutshell, crops-livestock integration practices allow the improvement of autonomy, internal recycling rate and the productivity of household farming system. Some aspects not covered in this research, such as the implication of crop-livestock integration for crop and livestock water productivity, for GHGs emission need to be investigated. Likewise, it is necessary to investigate the best combination crop-livestock integration for a sustainable farming in Burkina Faso.

Another study on the co-construction of innovative farming system for crop-livestock integration in the South-western region of Burkina Faso was conducted by Sawadogo (2018). The purpose of this study was to develop with stakeholders innovative crop-livestock integration in the study area. In this perspective, the author used a participatory approach combined with an Agent-Based Modelling. The study approach allowed to provide a relevant framework to formulate and assess the impacts of policies in short and long terms. Indeed, it gives an opportunity for an ex-ante analysis of policies that formulation and implementation are difficult and expensive. The author found that: (i) the main stakeholders of CLI are either direct (producers, state extension services, farmers organisations, technical partners) or indirect (consumers, traders, transporters, customary authorities and technical partners); (ii) CLI has been impacted in the past by both social factors (lightening the work of agriculture and satisfaction of cultural values, public institution advised crop-livestock integration) and environmental factors (climatic hazards and space sharing); (iii) in the future the factors that will affect CLI are: demography, climate change, profit research, agriculture intensification and institutional support, the last two being the most uncertain. Some aspects not treated in this study such as the factors determining the sustainable combination of crop and livestock production need to be investigated. Indeed, it is important to check beyond the productivity, GHG emissions, soils properties and water productivity within an integrated crop-livestock system.

Rigolot et al. (2017) conducted a study on the "Interactions between intervention packages, climatic risk, climate change and food security in mixed crop–livestock systems in Burkina Faso". The purpose of this study was to quantify the benefits and trade-offs from alternatives intervention scenarios to adapt to climate change and variability for two different farms type (larger & small) in northern Burkina Faso. Specifically it consisted in evaluating the effect of climate change and variability on energy production and income generation at farm level under different combinations of interventions scenarios. Three models (APSFarm, LivSim, IAT) were used to simulate scenarios and derive the impacts of climate variability and change on crops, livestock production and farm household level. The authors fount that : (i) for small farms and all scenarios there is a deficit in the average energy production (lower than household requirement) and agricultural income was below the poverty line (1.25 USD/capita/day). Conversely, for large farm and for all interventions scenarios average energy is more than double of households' requirements and the total agricultural gross income ranges from 4.64 USD/capita/day to 6.23 USD/capita/day according to these scenarios.

Against the background of the higher emission scenario (RCP 8.5), climate change could strongly limit crop and livestock production both for small and large farms in northern Burkina Faso, with a higher impact on small farms. Climate impacts were higher on livestock on the small farm, due to the threshold effect on feed resource available. Moreover, large farms had more sheep that are less climate sensitive than cattle and for small farm climate change could totally suppress the profitability of some intervention and significantly increase associated downside risk. Finally, the authors suggested that synergies and complementarities in mixed crop-livestock systems should be fully exploited by considering these systems as a whole instead of focusing of their components: This would allow a better adaptation strategy to climate variability and change. This study, however, did not consider how crop-livestock system can act as a resilience strategy to climate change.

Bénagabou et al., (2013), conducted a research on the effect on crop-livestock integration on energy efficiency of farms in agro-pastoral systems in Burkina Faso. The main objective of this study was to contribute to the promotion of more efficient production systems. To achieve this aim, the authors have undertaken surveys of traditional and modern farms in both rural and peri-urban areas. Statistical data analysis consisted in Principal Component Analysis, Hierarchical Cluster Analysis and Analysis of Variances. The authors found that energy efficiency varies according to the farming system, modern farms being less energy efficient than traditional farms. Also, crop-livestock integration is observed impacting positively energy efficiency in traditional farms; whereas it was causing a decrease in energy efficiency in intensive dairy production farms. Indeed, unlike intensive dairy farms, a strong

CLI induced an increase by 3.3 and 1.1 of energy efficiency for crop oriented and livestock oriented farmers respectively. Conversely, in intensive dairy production farms, there was a decrease in energy efficiency of 0.2. Moreover, the authors pointed out that CLI adoption lessened fossil energy utilisation. Indeed, using draft power reduces fossil fuel and electricity power utilisation. Similarly, the use of crop residues and organic fertilizer reduced the utilisation of concentrate feed manufactured using fossil energy, and of chemical fertilizer. Therefore, CLI could be an alternative for environmental protection through the reduction of GHGs emission even if livestock constitute a source of methane pollution. The authors pointed out the necessity to deepen research studies on the production systems in Burkina Faso given that the sole energy performance is not sufficient to ensure enough characterisation of these production systems. Thus, investigations have to be made to identify the level of CLI that emit less GHGs, that have a good level productivity including crops and livestock water productivity and preserve or improve soil fertility. Furthermore, the authors were able to characterise crop-livestock integration in terms of high and low integration. A complementary investigation is suitable to give more characterisation of crop-livestock integration in terms of partial or total integration, ineffective or effective and inefficient or efficient integration. The Global crop-livestock integration indicator (GI) designed by the authors can hide some information. Indeed a value of GI of 100 % or more do not give information on the effectiveness and the efficiency of the integration. The analysis did not consider the effectiveness in the coverage of the needs in crop-residues, animal manure and draft-power in the integrated crop-livestock system. Moreover, the way of attaining the effectiveness of integration need also to be investigated in a sense that if efforts more than necessary are deployed to achieve it; the integration cannot be efficient.

A study was conducted by Andrieu et al. (2015), in Koumbia, a village located in the sub-humid agro-pastoral zone of Burkina Faso. The aim was to explore the multi scales (field, farm, village) impacts of alternative utilisation of crop residue on crop and livestock productivity. Thereafter, the trade-offs of crop residues utilisation were also quantified through the analysis of different crop and livestock production and soil fertility indicators. The methodology of the study consisted of surveys and a mass flow model used to compare the current crop residues management practices (reference situation) with alternative scenarios of farmers private cereal crop residue uses. The first scenario assumes a collection and composting of crop residues by individual farmers; while the second assumes the collection of crop residues from the field and their utilisation by individual farmers as fodder for livestock during the dry season. The authors found that there were slightly positive synergies at the farm scale between crops and livestock activities regarding the current utilisation of crop residues within the study area. Conversely, following the two scenarios, the authors found, trade-offs between cereal crop residue uses. Indeed, improving crop productivity at farm level through the use of compost from residues, will affect fodder self-sufficiency and the nutrient balance on a wider scale. This research work showed challenges that crop-livestock integration practices are facing or could experience in West Africa and within Burkina Faso in particular. Therefore, there is a need for sound and suitable articulation of the two components of the system (crops and livestock) in order to minimize the trade-offs of crop residues uses by each component. There is also a need to investigate the role of crop-livestock integration for the sustainability of agroecosystems in Burkina Faso and within West Africa in general.

#### 2.4.1.2 Crop-livestock integration assessment, ecological intensification and sustainability

Bénagabou (2018) proposed indicators to characterise crop-livestock integration for a diversity of mixed farming in Burkina Faso. These indicators based on the three pillars (manure, crops residues, drought power) of the integration defined by (Landais and Lhoste, 1990) consisted of: (i) coverage of manure need; (ii) coverage of fodder need; (iii) coverage of animal traction need. The three indicators contribute to a global indicator (GI) given an idea on the strength of crop-livestock integration in the farming system.

More information is needed on these crop-livestock integration indicators (defined in terms of high and low level of integration indicators by the authors), to have a complete overview of the integrated system beyond the physical or technical integration based on fodder, manure and animal energy uses. In fact, besides the technical integration, there is also the reinvestment of incomes derived from livestock component to the cropping component and vice-versa. This gives an overview of the contribution of financial resources to the effort of crop-livestock integration within agro-systems in Burkina.

Vall et al., (2011), studied crop-livestock integration and ecological intensification in agrosilvopastoral systems in western Burkina Faso. The study aimed at: (i) characterizing main strategies and the contribution of CLI in the farming intensification; (ii) evaluating the contribution of CLI in the ecological intensification through the increase in productivity while maintaining soil fertility. Using sampled farming households with different typologies dependent on their herd size and area cultivated, key data generated were related to livestock and cropping activities, manure production, exchanges of organic manure and crops residues. Data analysis was performed through Principal Component Analysis (PCA) that allowed farm diversity analysis. In order to characterize homogenous clusters of farms a Hierarchical Cluster Analysis (HCA) was performed; and an ANOVA test was conducted to compare different clusters with regard to the farm structure, the level of crop-livestock integration, the mode of organic matter production, the level of intensification and the technico-economic performances. Clusters' means for each variable were discriminated using the Test of Newman-Keuls at 5 % confidence level.

The authors found that CLI allowed diversification of farming households' incomes and improved savings. Moreover, CLI reduced the risks of exposure to climatic hazards and economic uncertainties. It also contributed to farming intensification by increasing the availability of animal energy for cropping and organic manure for fertilisation. Furthermore, it contributed to ecological intensification through an increase in the ratio of organic fertilizer to the cultivated area and in that of crop residues to Tropical Unit Livestock. CLI practices were more adopted by smaller farmers that were oriented to crop production. These practices improved their farm economic performance, maintained soil fertility and reduced their exposure to food insecurity. More investigations beyond the findings of these authors is needed to provide more insight to decision makers for a sustainable farming in Burkina Faso. It is in this perspective that the current research will focus on the implications of CLI system on water use efficiency, carbon stock and potential GHGs emissions from the integrated system.

A research was conducted by Vall et al. (2017) on the "intensification pathways and sustainability of crop-livestock systems in Sub-Saharan Africa: crop-livestock interaction contribution". The research sought at investigating the contribution of crop and livestock integration to production intensification and farm sustainability. Three farmer typologies dependent on the size of area cultivated and cattle herd size were investigated: livestock farmers, crop farmers and agro-pastoralists. The level of crop and livestock interaction was evaluated based on the amount of carbon retained annually on the farm in the form of organic manure and stocks of crop residues for fodder use (cereal straw, legume tops) and livestock feed (cottonseed cake, cereal bran). The level of crop-livestock interaction was examined in the technico-economic, food security and environmental contexts. The authors found that all the three farmer typologies were practicing crop and livestock association but in different ways depending if the farm is livestock or crop oriented. The medium and large crop farmers were characterized by an increase in cultivated area whereas big breeders were characterized by an increase of the herd size. Conversely, agro-pastoralists were characterized by an increase in herd size and cultivated area. A relative stagnation was observed for small farmers and small breeders. Three intensification pathways were identified : (i) the first consisting of a low cost intensification and supporting feeding of small and medium livestock; (ii) the second consisting of crop-livestock association oriented toward organic manure production as complement to chemical fertilizer used by big farmers and agro-pastoralists; (iii) the third one consisting of a passive intensification strategy based on livestock stocking and direct crops residues grazing on breeders' fields. Definitely, it was found that farm with high level of crop-livestock association had the biggest area and presented the best sustainability indicators including technico-economic, environmental and food security indicators. Beyond these findings there is a need to look at the emissions of GHGs from crops-livestock systems, the crop and livestock water productivity, soil fertility and carbon stock in the integrated system.

A research work was conducted by Vall et al. (2006), within west of Burkina Faso to investigate the challenges induced by changes that occurred due to the increase of anthropogenic pressure on agricultural, forest and pastoral resources. The authors indicated that the increasing competition among resources users, for farmland and pasture led to more tension and conflict between pastoralists and crop farmers. The authors studied the mode of intensification and crops-livestock integration for: livestock farmers, crop farmers and agro-pastoralists. Despite, the increasing trend of crop-livestock integration by these units, losses (>60 %) of crops residues and organic manure remain still worrying in the Region. This shows that in Burkina Faso, crop-livestock integration can still be improved. Improvement actions could be : (i) nutrients recycling and increase in fodder availability. This can be done through fodder cropping or an association of a cereal (maize, sorghum) with a multiple-purpose fodder crop (usually a legume), a way that responds to space and labor constraints and simultaneously increases fodder production and soil fertility; (ii) more rational use of crop and livestock co-products. This is possible through animal manure production techniques adapted to the size of the herd (manure barn, animals lairaging techniques); rational recycling of tops, straws and stems by withering the noble fractions for fodder use; controlled fruitless grazing, then composting of residues which cannot be grazed by the livestock (lower parts of cereal straw, cotton stalks); (iii) valuation of animal draw power. In a nutshell, for the authors, reinforcing exchanges between crop and livestock is a springboard for more sustainability and productivity of farming units. Definitely, the above mentioned actions can be solutions to address socioeconomic crises between the users of agro-pastoral resources. This research gave an overview of the role that the integrated crop-livestock system can play in productivity and sustainability enhancement. This study did not cover the GHGs fluxes within the integrated crop-livestock system in Burkina Faso.

Vall et al. (2019), conducted research on the co-design of innovative mixed-crop-livestock systems in the cotton-growing zone of Burkina Faso exposed to high variability in rainfall and volatility in the prices of agricultural products. This gives room to production diversification and mixed-crop-livestock farming with less inputs in order to ensure food security and reduce economic losses. In their study three main categories of farming units were considered: crop farmers, agro-pastoralists and livestock farmers. Herd and cultivated areas sizes experienced until now an increase both for agro-pastoralists and livestock keepers while small crop farmers experienced herd decapitalization. The authors found an increase of organic manure production used on maize and cotton; a systematic gathering of crop residues and fodder production at a certain extent. Innovation in organic manure production is facing transportation challenges from household to the farm. The alternative proposed by the authors was to produce directly organic manure in the field using concrete compost pits without any transportation and returning cost of the compost in such pit. Generally, in the Western Burkina Faso, mixed-crop-livestock system is not yet suitably practiced to fully play its role of agro-ecological transition. Indeed, farmers are still attached to chemical fertilizer utilization associated to crop-livestock integration. With regards to the authors findings, it appeared that the agro-ecological transition despite its advantages is still confronted with strong adoption of conventional production systems promoted by cotton companies and the difficulties observed in the implementation of some innovations. Research oriented to investigate more the related advantages of mixed-crop-livestock system could give more incentives to farmers to opt and engage favorably into the agro-ecological transition. It is in this perspective that the current research work aims at investigating the role of crop-livestock integration as a resilience strategy to climate change in Burkina Faso.

## 2.5 Developments in greenhouse gases emission and removal

West African countries' agriculture constitute an important source of GHGs emissions. Indeed, the emissions in West Africa represents 20 % of the total emissions against 11 % of the total emissions in each of Central and North Africa. The biggest amount of emission is from Agricultural Forest and other land use (AFOLU) Sector (Tongwane et al., 2016; Tongwane and Moeletsi, 2021; Zervas and Tsiplakou, 2012). Farming systems in West African countries in particular, are characterised by a generally bad manure management usually left in solid form on pastures and ranges. This results in the generation and emission of methane into the atmosphere which contributes adversely to climate change. At the same time, these countries are heavily dependent on wood-fuel as their primary source of fuel which leads to deforestation (Arthur and Baidoo, 2011) with subsequent release of carbon dioxide.

The increase of atmospheric greenhouse gases concentrations in the region, may cause global warming and the major incriminated greenhouse gases involved carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) and chlorofluorocarbons. The main sources and types of greenhouse gases from livestock systems are $CH_4$ from enteric fermentation and manure management, $CO_2$ from land use and its changes and $N_2O$ from manure management (Zervas and Tsiplakou, 2012). The general increase of food demand on the continent and abroad, the intensification of agricultural production with additions of more inputs of synthetic fertilizer, and expanding agricultural lands are the major factors that cause this rapid growth of emissions (Tilman et al., 2011; Tongwane & Moeletsi, 2018). Enteric fermentation is the largest source of emissions from agriculture in the continent with more than half of the total agricultural emission (Tongwane & Moeletsi, 2018).

Despite the increase in greenhouse gases emissions in West Africa and in Burkina Faso in particular, their quantification remains until now problematic due to the lack of emission factor adapted for the region. Indeed, in general greenhouse gases quantification uses emission factors calibrated with respect to temperate conditions that could lead to emission under or over-estimation (Zhu et al., 2016) under tropical conditions (Boateng et al., 2017). Therefore, an important research gap to be rapidly fill consists of the determination of local emission factors adapted for West Africa. This will allow a more accurate estimation of greenhouse gases emission from mixed-crop-livestock farming systems within Burkina Faso and West Africa in general.

Greenhouse gases can be estimated following three approaches (tiers) provided by the Intergovernmental Panel on Climate Change (IPCC) including the Tier 1, Tier 2 and Tier 3 approaches (Eggleston et al., 2006; Zhongming et al., 2019). A generic Tier 1 approach is recommended for countries that do not have local emission factors; Tier 2 requires country-specific emission factors; and Tier 3 is applied when there are detailed emission factors measured according to environmental and management conditions of a location. Tier 1 approach is adequate for large-scale studies but erroneous for detailed GHG calculations Tongwane and Moeletsi, 2021). This approach is a simplified approach that relies on default emission factors defined and is likely to be suitable where enhanced characterisation data are not available. Moving from Tier 1 to Tier 2 or Tier 3 method implies more accurate estimation of greenhouse gases emission but much more exigence for additional country-specific information on activity data (Zhu et al., 2016). For example the Tier 3 approach could employ the development of sophisticated models that consider diet composition in detail, concentration of products arising from ruminant fermentation, seasonal variation in animal population or feed quality and availability, and possible mitigation strategies. Many of these estimates would be derived from direct experimental measurements (Tongwane and Moeletsi, 2021).

## 2.6 Development in water productivity

Worldwide, many regions are characterized by a considerable scope for physical water productivity improvement. This improvement could be achieved by many farmers from developing countries through the adoption of proven agronomic and water management practices contributing in land productivity enhancement. Water productivity improvement constitutes a pathway for poverty alleviation in most of these countries. The main reasons of improving agricultural water productivity are: (i) the satisfaction of the raising food demands of a growing population in the light of water scarcity; (ii) the response to the pressure of water reallocation from agriculture to cities use and ensure the water availability for environmental use; (iii) the contribution to poverty reduction and economic growth. Indeed, an adequate use of water by poor farmers can improve nutritions and provide more incomes for the household (Molden et al., 2007). In this perspective the increase of water productivity is associated with food security and livelihoods (Cai et al., 2011; Cook et al., 2009). Therefore, particular attention must be paid to water resources utilisation in developing countries and generally within SSA must be paid a particular attention. The current annual agricultural evapotranspiration of 7,130 cubic kilometers is likely to nearly double in the future due to an inappropriate use of water (Molden et al., 2007). Moreover, these authors indicate that water productivity is also driven by non-water factors such as fertilizer use and labour. Much more, land degradation and nutrient depletion significantly constrain opportunities to increase water productivity. Indeed, nutrient limitation more than water availability is responsible for low water productivity (Breman et al., 2001). Furthermore, Bouman (2007), indicates that taking away water stress will not improve water productivity unless other stresses (nutrient deficiencies, weeds and diseases) are also alleviated or removed. Definitely, water management must be done concomitantly to nutrients, pest and soils managements to sustain water productivity (Rockström et al., 2010; Rockström and Barron, 2007). Therefore, there is a need of combining in a synergistic interaction water practices that increase access to water at the suitable period and other agronomic practices such as maintaining soil health and fertility, controlling weeds and diseases, and timing planting (Haileslassie et al., 2009; Molden et al., 2007). It is in this perspective that Ouattara et al. (2017), conducted a study to investigate the effects of soil and water conservation (SWC) and soil fertility management on maize yield and its water productivity. The authors sought at comparing yield and water productivity obtained under different soil water conservation practices coupled with different level of fertilizer applications. The authors found that in South Sudan zone with high rainfall (>1000mm/year) SWC practices had a limited effect on yield and water productivity. Conversely within North Sudan the combination practices improved significantly both maize yield (113 %) and water productivity (106 %). To go beyond the results of this study, the present research sought at investigating the effects of crop-livestock integration on maize, millet and rice yields and their water productivity across three agro-ecological zones of Burkina Faso. The findings of such research will give adequate information to policy makers and more incentives to farmers regarding their farming options.

Water productivity can also be, improved by influencing evapotranspiration. This can be done through the adoption by farmers of varieties resistant to diseases, salinity and drought and of early maturing varieties to shade soil surface and reduce high evaporation. Indeed, the amount of water evaporated is a function of climate, soils and the extension of crop canopy shading soil surface. Thereby, evaporation can be a very high share of evapotranspiration in rain-fed system with low plant densities; whereas productive transpiration can be improved through mulching, ploughing, early crop cover establishment in order to shade the ground as rapidly as possible, reduce evaporation and increase productive transpiration (Molden et al., 2007). Similarly productive evapotranspiration can be improved by reducing transpiration from weeds. This allows the reduction of soil moisture depletion on crop land.

The highest potential of water productivity gains can be achieved in low-yielding rain-fed areas across SSA (Rockström et al., 2010). Given that the world's poorest people live within such low-yielding areas, improving water and land productivity in those areas, will ensure multiple benefits such as the limitation of agricultural land expansion and the improvement of the poorest households' livelihood (Descheemaeker et al., 2013), without threatening other ecosystems services (WRI et al., 2008).

In a mixed crop-livestock agroecosystem, livestock water productivity (LWP) represents an important component in improving overall productivity of the system (Mekonnen et al., 2011). LWP relies mainly on water demands for feed production (Haileslassie et al., 2009a) given that livestock drinking water requirements are comparably negligible (less than 2 % of water required for feed production) (Peden et al., 2009; Peden et al., 2007). Indeed, the improvement of LWP will rely on that of feed water productivity that can be done significantly through the reduction of evaporation component of evapotranspiration. In terms of feed sourcing, crop residues and by-products constitute unique opportunity that require no additional evapotranspiration. Taking advantage of such feed, huge gains in LWP are possible

(Peden et al., 2007). These authors indicated a positive correlation between LWP and the share of animal diets composed of crop residues and by-products. Furthermore, they indicated that whenever, livestock are fed crop residues and graze rangelands unsuitable for cropping, livestock make a very efficient use of the available water. In this perspective, farming systems should promote the use of crop residues and by-products as animal feed sources. But this should be done in an optimal way such that a certain quantity of residues may return to the soil to maintain and improve its fertility. Indeed, the trade-off between the uses of crop-residues for livestock feeding and soil fertilisation has to be sufficiently studied and an optimum utilisation level must be found for productive water use at the system scale (Gebreselassie et al., 2009). Moreover, there is a likelihood of under-utilisation of feed resources due to the lack of drinking water for animal within some rangelands and drier rain-fed areas. Feeds that are produced and not consumed by livestock constitute a major loss of potential benefits and productivity of agricultural water (Peden et al., 2007). In such situation, strategies should be implemented to increase feed consumption by livestock. Mixed-crop-livestock system coupled with efficient water harvesting and management techniques can be an opportunity.

Beside the utilisation of crop residues, livestock water productivity is also influenced by management practices, livestock age and weight, other feed types (Gebreselassie et al., 2009a) and their conversion rate into animal products (Figure 2.3) (Peden et al., 2007a). Adjusting such factors will contribute to increasing gains in livestock water productivity (Molden et al., 2007). Subjected to various drivers, livestock production systems are rapidly changing; that calls for a constant adaptation of policy, investment and technology options. There is an urgent need to improve LWP to meet the increasing populations' demands for animal products and face the increased global water scarcity and competition for water. This can be done through three main innovative interventions: (i) feed related strategies consisting of feed selection and their quality improvement; sustainable grazing lands management; an increase in feed water productivity; (ii) water management strategies consisting of water conservation and harvesting; (iii) animal management strategies consisting of breeds improvement; meeting livestock feed requirement; diseases prevention and control; appropriate livestock watering (Figure 2.3) (Peden et al., 2007). All these strategies contribute in reducing non-productive water depletion.

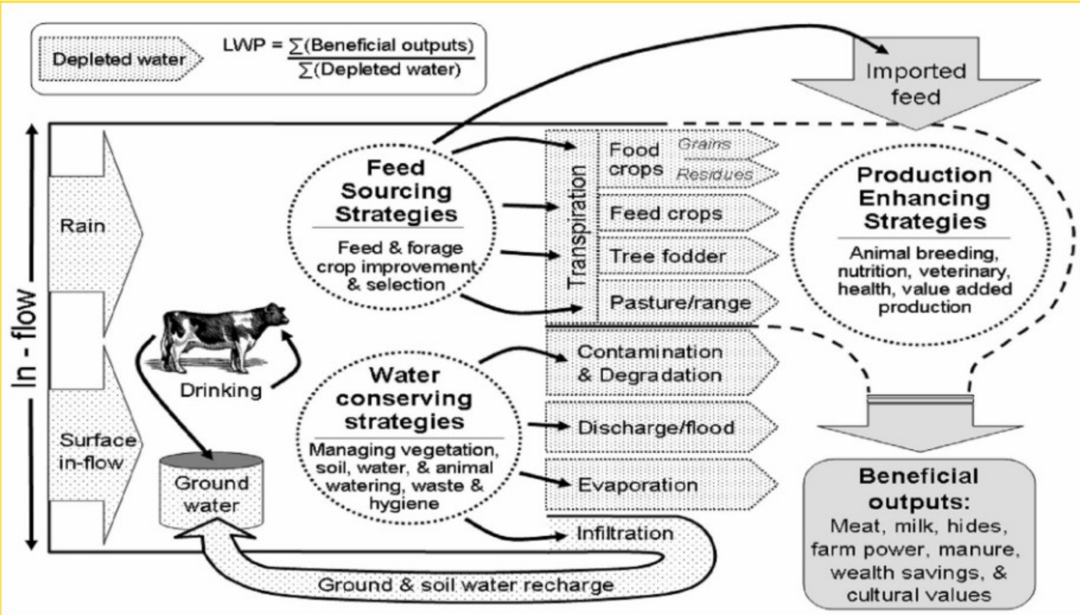

Figure 2.3: Simplified framework for assessing livestock-water productivity for options identification to reduce water depletion and increase of goods and services associated with animal keeping: Source: Peden et al. (2007).

Gebreselassie et al. (2009) in their research indicated that in order to produce one (1) litre of milk and one kilogramme of meat, ~1.0 $m^3$ and ~11.5 $m^3$ of water were required respectively. They also found that LWP is higher for large livestock than the smaller one. Finally, the authors indicated that feed composition influence LWP.

In several studies, LWP computation considered key products and services from livestock (Peden et al., 2009). These key products refer to meat, milk, hides, manure while services consisted of the provision of farm power and transportation. Despite the numerous methods proposed in the literature to compute LWP, this is not a straightforward task. For Peden et al. (2007), there are many limitations in the estimation of water use by livestock. Some of the major limitations are : (i) high biophysical and socio-economical variability in livestock production system given room to knowledge gaps not favourable to LWP estimation; (ii) existence in developing countries of large herds size with low production performances in a way that water depleted by animals is associated by their maintenance rather than their productions; (iii) likelihood of underestimating LWP because often, the multiple uses of livestock is ignored, focusing only on milk and meat production.

Comparatively, more studies were conducted on Crop Water Productivity than Livestock Water Productivity and few were interested in the implications of crop-livestock integration in the farm water productivity. The current research will investigate on how mixed-crop-livestock system can benefit water productivity and food security in the face of climate change. Indeed, water productivity is very climate dependent in the sense that increase in temperature consecutive to the global warming, offsets water productivity gains (Molden et al., 2007). Therefore, there is an urgent need of alternatives to produce more food and feed per drop in a context of climate change and water scarcity for the majority of SSA countries and Burkina Faso particularly. The following section will analyse climate trend in the country over the last sixty years.

# CHAPTER 3: CLIMATE CHANGES AND VARIABILITY ACROSS THREE CLIMATIC ZONES OF BURKINA FASO


## ABSTRACT

Climate change and variability in the Sahel region have significantly reduced agro-pastoral production systems' output. Analysing daily climatic data for Burkina Faso spanning 60 years (1961 – 2020), this study investigated the implications of climate change and variability on food production in three (3) agro-climatic zones of Burkina Faso: Sahel (Dori), Sudan-Sahel (Niou) and Sudan (South Dano). The analysis compared annual rainfall and temperature over four climatological periods (1961-1990, 1971-2000, 1981-2010 and 1991-2020) for these three (3) zones. In addition, the seasonal means of rainfall and temperature were computed and compared over two climatological periods, 1961-1990 and 1991-2020. Climate indices were computed and analysed using the package ClimPACT2 GUI in R software version 3.0.2 (R core team 2021). The climatic indices were further subjected to a Principal Component Analysis (PCA). Rainfall showed more variability with some changes in its patterns within the study sites, while changes in temperature and related indices were more pronounced. The last three decades of 1961-2020 distinguished themselves by hot climate extremes from the first three decades that were globally characterized by cold climate extremes. Moreover, recent decades have been wetter. The trend analysis and PCA results show that climate change and variability are more pronounced in the Sahel and Sudan-Sahel zones than in the Sudan zone of Burkina Faso.


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**Key words:** Climate change, climate indices, Burkina Faso, West African Sahel.

## 3.1 Introduction

Global climate change constitutes a vital challenge worldwide and may still remain a challenging issue in the future for a sustainable development (IPCC, 2001b). Indeed, climate conditions have experienced important changes over the 20$^{th}$ century. This period revealed an increasing trend of both the global mean surface temperature (Salack et al., 2015; Sarr et al., 2015; Sylla et al., 2016b; Wedajo et al., 2019; Worku et al., 2022) and precipitations (Nouaceur and Murarescu, 2020; Sultan and Gaetani, 2016; Wedajo et al., 2019). However, at the regional or local scale, both increases and decreases in the spatiotemporal trends of precipitations are seen (Atiah et al., 2021; Berg and Sheffield, 2018; Elfaig et al., 2013; Nicholson, 2005, 2000). Regarding climate extremes, hot days/heat index and cold/frost days experienced increased and decreased trends for nearly all land areas during this century (Coumou and Robinson, 2013; IPCC, 2013, 2001b; Sillmann et al., 2013). For the future climate, models predictions similarly indicated a global increased trend in temperature (IPCC, 2007b; Porter et al., 2014; Salack et al., 2015; Sylla et al., 2016a, 2016b) and precipitations (Akinsanola and Zhou, 2019; Ohba and Sugimoto, 2019; Sylla et al., 2016b).

West Africa is a climate change hotspot region characterized by high climate variability with extreme climatic events, severe exposure and low adaptive capacity (Heubes et al., 2013; Hummel et al., 2012; IPCC, 2013). Climate change in this region negatively impacts agricultural production (Nelson et al., 2018) and strongly affects the well-being of poor households who depend on natural resources (Denton et al., 2001; Jones and Thornton, 2009) and cropping.

The case of Burkina Faso is not an exception where evidence suggests that the country is experiencing climate change as characterized by warming, localised monsoonal precipitation recovery and an increase in the occurrence of climate extremes (De Longueville et al., 2016; El Bilali, 2021; Kima et al., 2015; Ly et al., 2013; Mahé and Paturel, 2009; Nicholson, 2005; Salack et al., 2015; Sylla et al., 2016b). However, climate change patterns in Burkina Faso are characterised, most of the time, by a much more pronounced change in temperature than in rainfall (Kima et al., 2015; Zampaligré et al., 2014). The agricultural sector is highly vulnerable to climate change due not only to its rainfall-dependent characteristics but much more to the excessive heating, namely within the arid and semi-arid zones of the country. Future climate change projections for the country (PANA Burkina, 2007) predict a decline in rainfall of 3.4 % by 2025, 7.3 % by 2050, and an increase in average temperature (about 0.8°C by 2025 and 1.7°C by 2050). Such changes may provoke: (i) a disruption of the agricultural calendar, or a reduction in agricultural yields (Sultan et al., 2019b), already confirmed by some studies in Burkina Faso (Kima et al., 2015; Zampaligré et al., 2014); (ii) the extinction of less-resilient species, water deficit, and the emergence of some pests (Yaméogo et al., 2018). Consequently, farmers and policy-makers need to be promptly informed about the clear patterns of climate change in the country. In such context, the computation and analysis of climate extremes indices can be of an important interest because they carry more information than the historical daily rainfall and temperature derived from them (Chisanga et al., 2017). Their analysis, could therefore allow a more reliable awareness of both farmers and policy-makers on the potential implications of climate deterioration for farmers' livelihoods in Burkina Faso.

While studies have been conducted on climate using historical climatic data to characterize the climate in Burkina Faso (see Kima et al., 2015; Zampaligré et al., 2014), the use of climate indices, which is the central focus of this study, has to date, not been adequately documented in Burkina Faso. It is against this background that the current study was undertaken to analyse climate extremes indices and give more detailed information to food security stakeholders (crop farmers, livestock keepers, policy-makers) in Burkina Faso.

We hypothesized that the three climatic zones of Burkina Faso have experienced significant changes in temperature and rainfall patterns from 1961 to 2020.

## 3.2 Materials and methods

### 3.2.1 Study area

The study was carried out across three climatic zones of Burkina Faso: the Sahel zone (between latitudes 12.91° and 15.07° and longitudes 2.84°W and 1.29°E), the Sudan-Sahel zone (between latitudes 11.12° and 12.93° and longitudes 4.35° W and 2.40° E) and the Sudan zone (between latitudes 9.40° and 12.02° and longitudes 5.41° W and 2.69° W), distributed along a gradient in Burkina Faso. The study sites were Dori (13°45'36"N / 14°19'12"N and 0°24'0"W / 0°16'12"E) in the Sahel zone, Niou (12°40'12" / 12°54'36"N and 1°58'48" W/ 1°41'24" W) in the Sudan-Sahel zone, and Dano (10°58'48" N/ 11°12'36"N and 3°6'36"W / 2°57'0"W) in the Sudan zone (Figure 3.1). The climate across the zones is tropical sub-arid to sub-humid with a unimodal rainfall regime. Livestock and crop farming represent the two main socio-economic activities in the study sites with some differences as we move northward from Sudan to Sahel. While the Sahel zone is more specialised in livestock rearing, the Sudan zone is known to have more suitable climatic conditions allowing farmers to practice crop farming. The Sudan-Sahel is the transition zone where farmers are able to effectively combine the two activities in their production system. In all cases, in each zone, farmers exploit environmental opportunities for choosing their activities.

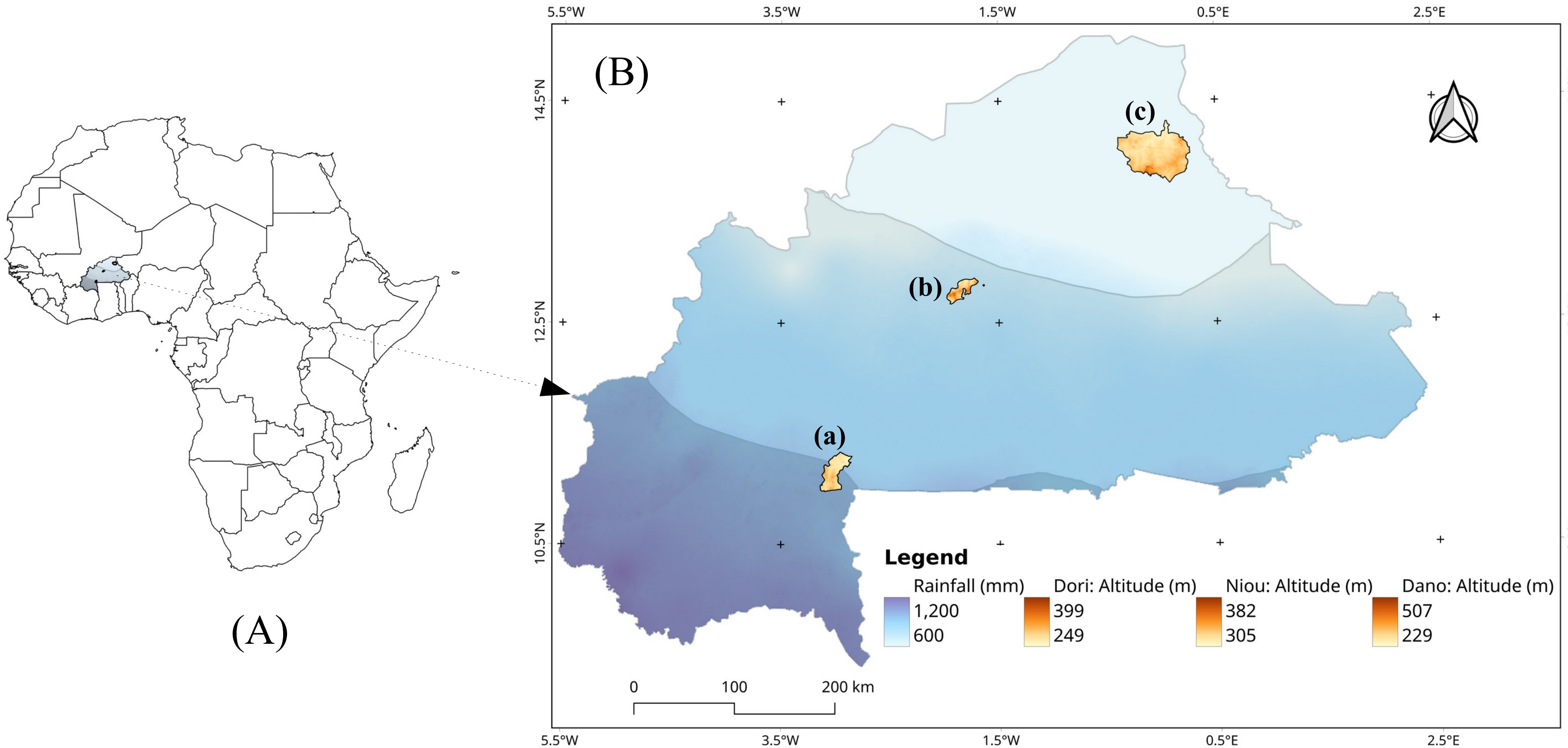


Figure 3.1: Location of study districts across climatic zones of Burkina Faso. (A) Map of Africa; (B) Map of Burkina Faso; (a) Dano District; (b) Niou District;(c) Dori District. Source: Sanou (2023).

The Walther-Lieth climate diagrams revealed a long-term mean annual total rainfall of 1077, 783 and 495 mm in Sudan, Sudan-Sahel and Sahel zones, respectively over the period 1961-2020. Over the same period, these zones also experienced mean annual temperatures of 27.8°C, 28.5°C and 29.6°C, respectively (Figure 3.2).

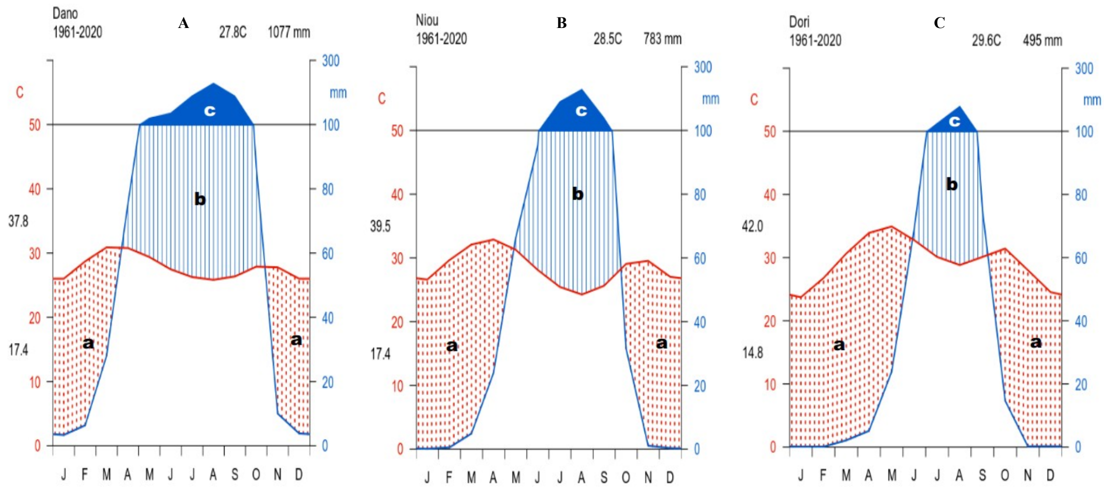


Figure 3.2: Walther-Lieth (1960) climate diagram for Sudan (Dano (A)), Sudan-Sahel (Niou (B)) and Sahel (Dori (C)) zones. Legend: (a) dry season, (b) rainy season, (c) major seasonal precipitation. Source: Author's Own Computation, 2023.

### 3.2.2 Data collection

Long time series climatic data spanning the last 60 years (1961-2020) were used. The data were obtained from the National Agency of Meteorology of Burkina Faso ("Agence Nationale de la Météorologie du Burkina Faso (ANAM)") and includes daily rainfall, daily maximum temperature and daily minimum temperature. The used dataset were compiled from the weather stations in the three climatic zones considered: Dori synoptic station for the Sahel zone, Ouagadougou synoptic station for the Sudan-Sahel zone and Gaoua synoptic station for the Sudan zone.

### 3.2.3 Data analysis

### 3.2.4 Daily climate variables analysis

Mean annual rainfall and temperature were computed for the time periods 1961-1990, and 1991-2020 and subjected to the independent t test to compare climate characteristics between periods in each zone. The data was statistically checked to meet the normality assumptions (Shapiro-Wilk test) and homogeneity of variance (Levene test).

In addition, to check seasonal changes in climate pattern, mean rainfall and temperature was computed over four seasons within each study zone: from December to February (DJF); March to May (MAM); June to August (JJA) and from September to November (SON). Mean seasonal rainfall and temperature of each year (1991-2020) were compared to that of the corresponding seasons of the reference period 1961-1990. This was done using the independent two-sample t-test. A graphical representation of seasonal rainfall and temperature was plotted using seasonal box-plots for each zone using R software.

#### 3.2.4.1 Climate extreme indices analysis

To assess climate extremes trends in each of the three climatic zones, twenty-three (23) climate indices known as best climate descriptors were selected among the 64 indices commonly used for climate trends analysis (Alexander and Herold, 2016). The first ten (10) out of the twenty-three (23) selected indices (Table 3.1) have important implications in the sectors of agriculture and food security, water resources and hydrology (Alexander and Herold, 2016). These indices were computed using the R package ClimPACT2 GUI (Alexander and Herold, 2016). We also considered other additional indices such as warm spell, cold spell, dry spell, wet spell, rainfall anomaly and intensity which better describes climate conditions in Burkina Faso where high temperatures and irregular rainfall strongly determine water flow and availability for cropping. Moreover, water availability for plant use is highly influenced by evapotranspiration, which is also influenced by temperature. To determine the importance of each selected index and the most affected decades in terms of climate deterioration within each climate zone, we first computed the mean values of climate indices over six decades (1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2010, 2011-2020). Climate indices were afterward subjected to Principal Component Analysis (PCA) using the R package 'FactomineR' (Lê et al., 2008). For this purpose, the time series of chosen indices were split and analysed according to the six defined decades within each climate zone.

Table 3.1: Characteristics of climate indices analysed in the study

| Indices | Definition | Plain language description | Importance |
|---|---|---|---|
| TXx (°C) | Warmest daily maximum temperature (TX) | Hottest day | AFS |
| TNn (°C) | Coldest daily minimum temperature (TN) | Coldest night | AFS, |
| TR (Days) | Annual count of days when TN > 20 °C | Days when minimum temperature exceeds 20°C | H, AFS |
| WSDI (Days) | Annual number of days contributing to events where 6 or more consecutive days experience TX > 90$^{th}$ percentile | Number of days contributing to a warm period (where the period has to be at least 6 days long) | H, AFS, WRH |
| CSDI (Days) | Annual number of days contributing to events where 6 or more consecutive days experience TN <10th percentile | Number of days contributing to a cold period (where the period has to be at least 6 days long) | H, AFS |
| CDD (Days) | Maximum number of consecutive dry days (PR < 1.0 mm) | Longest dry spell | H, AFS |
| SPEI 12 | Measure of "drought" using the Standardised Precipitation Evapotranspiration Index on time scales of 12 months. | A drought measure specified using precipitation and evaporation | H, AFS, WRH |
| SPI 12 | Measure of "drought" using the Standardised Precipitation Index on time scales of 12 months. | A drought measure specified as a precipitation deficit | H, AFS, WRH |
| PRCPTOT (mm) | Sum of daily PR >= 1.0 mm | Total wet-day rainfall | AFS, WRH |
| R20mm (Days) | Number of days when PR >= 20 mm | Days when rainfall is at least 20 mm | AFS, WRH |

| | | | |
|---|---|---|---|
| SDII (mm/d) | Annual total PR divided by the number of wet days (when total PR >= 1.0 mm) | Average daily wet-day rainfall intensity | NE |
| R10mm (Days) | Number of days when PR >= 10mm | Days when rainfall is at least 10mm | NE |
| TX10p (%) | Percentage of days when TX <$10^{th}$ percentile | Fraction of days with cool day time temperatures | NE |
| TX90p (%) | Percentage of days when TX > $90^{th}$ percentile | Fraction of days with hot day time temperatures | NE |
| TN10p (%) | Percentage of days when TN <$10^{th}$ percentile | Fraction of days with cold night time temperatures | NE |
| TN90p (%) | Percentage of days when TN >$90^{th}$ percentile | Fraction of days with warm night time temperatures | NE |
| TMm (°C) | Mean daily mean temperature | Average daily temperature | NE |
| TXm (°C) | Mean daily maximum temperature | Average daily maximum temperature | NE |
| TNm (°C) | Mean daily minimum temperature | Average daily minimum temperature | NE |
| TNx (°C) | Warmest daily TN | Hottest night | NE |
| TXn (°C) | Coldest daily TX | Coldest day | NE |

| | | | |
|---|---|---|---|
| DTR (°C) | Mean difference between daily maximum temperature (TX) and daily minimum temperature (TN) | Average range of daily maximum temperature and daily minimum temperature | NE |
| CWD (Days) | Maximum annual number of consecutive wet days (when PR >= 1.0 mm) | The longest wet spell | NE |

H=Health, AFS=Agriculture and Food Security, WRH=Water Resources and Hydrology and NE= Non-evaluated against specific sector.
Source: Alexander and Herold (2016).

## 3.3 Results and Discussion

### 3.3.1 Annual rainfall

Sahel (Dori) and Sudan (Dano) zones did not show a significant difference in annual mean rainfall over the two climatological periods considered (1961-2020 and 1991-2020). In the Sudan-Sahel zone (Niou), rainfall patterns were significantly different ($p<0.05$) between the periods 1961-1990 (785.0±161.7mm) and 1991-2020 (780.9±117.9mm), showing a reduction of 4.1mm over time (Table 3.2). Similarly, a decreasing trend in the annual rainfall amount was indicated by previous research in Burkina Faso (De Longueville et al., 2016) in West Africa (Klutse et al., 2018) and worldwide (Alexander et al., 2006). Despite the reduction indicated in rainfall patterns, annual rain resumption was noticed both in Sudan-Sahel and Sahel zones of Burkina Faso since year 1982. This is consistent with several studies that revealed rainfall recovery in recent years over West Africa, including Burkina Faso (Biasutti, 2019; Bichet and Diedhiou, 2018; Crawford et al., 2016; Sylla et al., 2016b; Kima et al., 2015; Lodoum et al., 2013). The future rainfall patterns may further vary across this region (El Bilali, 2021) from the robust predicted change in rainfall with less rain in the Western part of the Sahel (Senegal, South-West Mali) and more rain in Central Sahel (Burkina Faso, South-West Niger) by 2060 (Sultan et al., 2014).

Table 3.2: Annual rainfall over three districts across three agro-climatic zones of Burkina Faso

| Climatic zones | Rainfall amount by periods (mm/y) | | |
|---|---|---|---|
| | 1961-2020 | 1961-1990 | 1991-2020 |
| Sudan (Dano) | 1075.0 ±162.6 | 1055.8±168.7[a] | 1097.7± 157.8[a] |
| Sudan-Sahel (Niou) | 783.3 ±139.2 | 785.0±161.7[a] | 780.9±117.9[b] |
| Sahel (Dori) | 494.9±125.3 | 484.1±134.8[a] | 506.5±118.5[a] |

Means with the same superscript along the rows at ($p<0.05$) are similar. Grey column present the means of the entire period. Source: Author's Own computation, 2023.

### 3.3.2 Annual temperature

Maximum and minimum annual mean temperature did not show the same patterns in all the zones from the periods 1960-1990 to 1991-2020 ($p<0.05$) (Table 3.3 and 3.4). Indeed, while the Sudan and Sudan-Sahel zones experienced a significant increase in the mean maximum temperature (by 0.4°C and 0.7°C respectively) from one period to the other, it is rather the Sudan-Sahel and Sahel zones that experienced a significant increase in the minimum mean temperature (by 0.7°C and 1.3°C respectively) from one period to the other. This could mean that the upward trend of minimum temperature drives climate change in northern Burkina Faso (Sahel). In contrast, the upward trend of maximum temperature may be the driver on changes within its southern (Sudan) regions. Finally, climate change in the transition zone (Sudan-Sahel) relies on the upward trend of both maximum and minimum temperature. Overall, the study findings aligned with previous literature (Easterling et al., 1997; Salack et al., 2015; Sylla et al., 2016b) that indicated an increasing trend of both maximum and minimum temperatures over West Africa.

Table 3.3: Annual average maximum temperature across three climatic zones of Burkina Faso

| Climatic zones | Maximum temperature by periods (°C/y) | | |
|---|---|---|---|
| | 1961-2020 | 1961-1990 | 1991-2020 |
| Sudan (Dano) | 34.0 ±0.4 | 33.8±0.4[a] | 34.2± 0.3[b] |
| Sudan-Sahel (Niou) | 35.2 ±0.5 | 34.8±0.4[a] | 35.5±0.4[b] |
| Sahel (Dori) | 37.1±0.5 | 37.2±0.5[a] | 37.3±0.4[a] |

Means with the same superscript along the rows at (p<0.05) are similar. Grey column present the means of the entire period. Source: Author's Own computation, 2023.

Table 3.4: Annual average minimum temperature across three agro-climatic zones of Burkina Faso

| Climatic zones | Minimum temperature by periods (°C/y) | | |
|---|---|---|---|
| | 1961-2020 | 1961-1990 | 1991-2020 |
| Sudan | 21.6 ±0.4 | 21.6±0.4[a] | 21.6± 0.4[a] |
| Sudan-Sahel | 22.2 ±0.6 | 21.8 ±0.5[a] | 22.5±0.5[b] |
| Sahel | 22.1±0.9 | 21.5±0.7[a] | 22.8±0.5[b] |

Means±sd with same superscript along the rows at (p<0.05) are similar. Grey column present the means of the entire period. Source: Author's Own computation, 2023.

### 3.3.3 Seasonal rainfall

Seasonal rainfall trends behave differently across the climatic zones, with very high variability from year to year and from one climatological period to another. Across all the climatic zones and for all the seasons, no significant difference was found in the rainfall pattern between the two climatological periods (1961-1990 and 1991-2020) p<0.05) (Figures 3.3a, b and c). Nevertheless, unlike the Sudan climatic zone, the Sudan-Sahel and Sahel zones showed a significant difference between seasonal rainfall in the last decade of the period 1991-2020, compared to the last decade of the 1961-1990 (p<0.05) (Figures 3.3b and c). This could mean the re-wetting during the last decade in the Sudan-Sahel and Sahel zones as indicated by previous Sahel region research (Alexander et al., 2006; Mahé and Paturel, 2009; Nicholson, 2005; Sylla et al., 2016b).

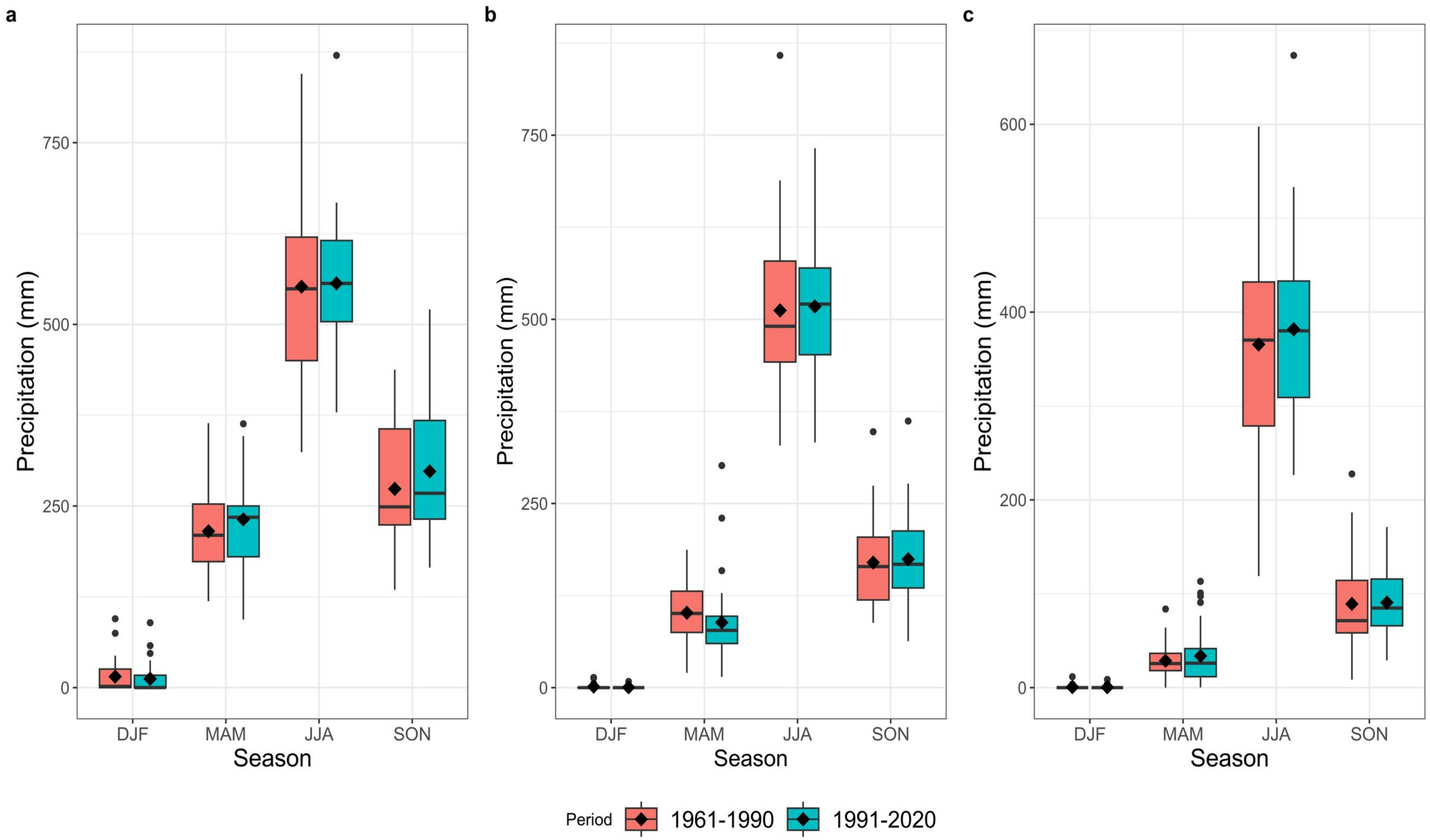


Figure 3.3: Seasonal rainfall (mm) over the periods 1961-1990 and 1991-2020 in Sudan (a), Sudan-Sahel (b) and Sahel (c) zones. Legend : DJF (December-January-February); MAM (March-April-May); JJA (June-July-August); SON (September-October-November). Source: Author's Own computation, 2023.

### 3.3.4 Seasonal temperature

Between the two periods (1961-1990 and 1991-2020), seasonal temperature was not always significantly different. A significant difference of both maximum and minimum temperature between the two periods was observed for all seasons (DJF, MAM, JJA and SON) ($P<0.05$) within Sudan-Sahel (Figure 3.4b; 3.5b) and Sahel zones (Figure 3.4c; 3.5c), however, this was not the case in the Sudan zone. The Sudan-Sahel experienced an increase by (+0.35°C; +0.9°C; +0.75°C; +0.63°C) and (+0.42°C; +1.07°C; +0.88°C; +0.72°C) in seasonal maximum and minimal temperature respectively from 1961-1990 to 1991-2020 ($P<0.05$). In the Sahel zone observed seasonal changes of the maximum and minimum temperature was (+0.12°C; 0.61°C; - 0.03°C; +0.21°C) and (+1.53°C; +1.53°C; +0.77°C; +1.37°C) respectively ($P<0.05$). In the Sudan zone, the minimum temperature did not show significant differences ($P<0.05$) between the period 1961-1990 and 991-2020 (Figure 3.5a). Inversely, the seasonal maximum temperature in the Sudan zone, experienced significant ($P<0.05$) changes by (+0.24°C; 0.49°C; - 0.61°C; +0.18°C) between the period 1961-1990 and the period 1991-2020 (Figure 3.4a). In general, all the three zones experienced an upward trend in seasonal temperatures. This corroborates the warming trend depicted by several research works in Burkina Faso and West Africa in general (Kima et al., 2015; Ly et al., 2013; NAP, 2015). Nevertheless, within the Sudan-Sahel and Sahel zones, changes in seasonal temperature were more perceptible in minimum temperature than in maximum temperature (Figure 3.9; 3.10; 3.11), similar to the findings of Panda et al. (2014). These changes in the temperature concerned all four seasons in all the zones. Thus, the growing season (June to

September) in all three zones has been continuously exposed to heat stress with its corollary of impacts on agro-pastoral productions in the studied zones.

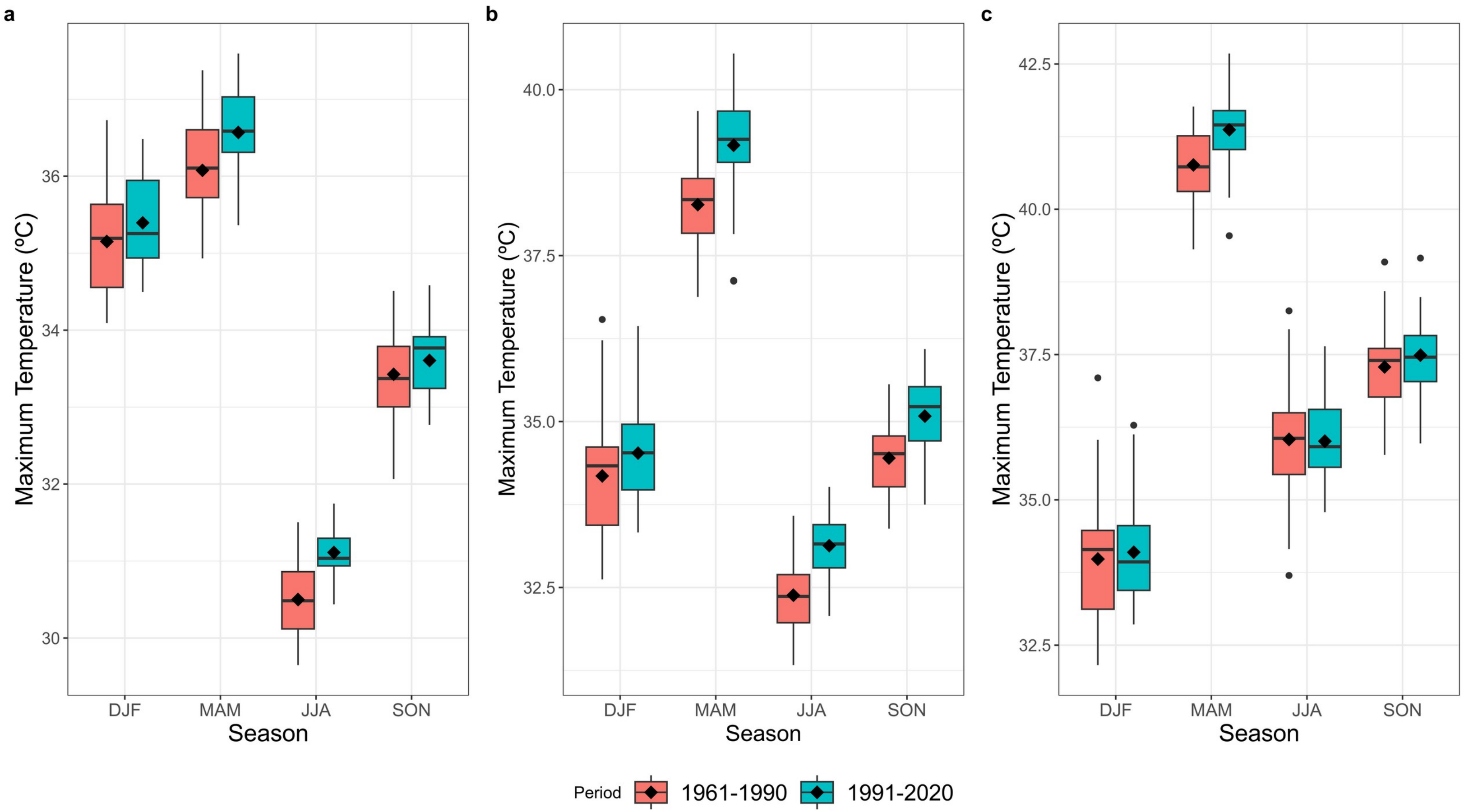


Figure 3.4: Seasonal maximum temperature (ºC) over the periods 1961-1990 and 1991-2020 in Sudan (a), Sudan-Sahel (b) and Sahel (c) zones. Legend : DJF (December-January-February); MAM (March-April-May); JJA (June-July-August); SON (September-October-November). Source: Author's Own computation, 2023.

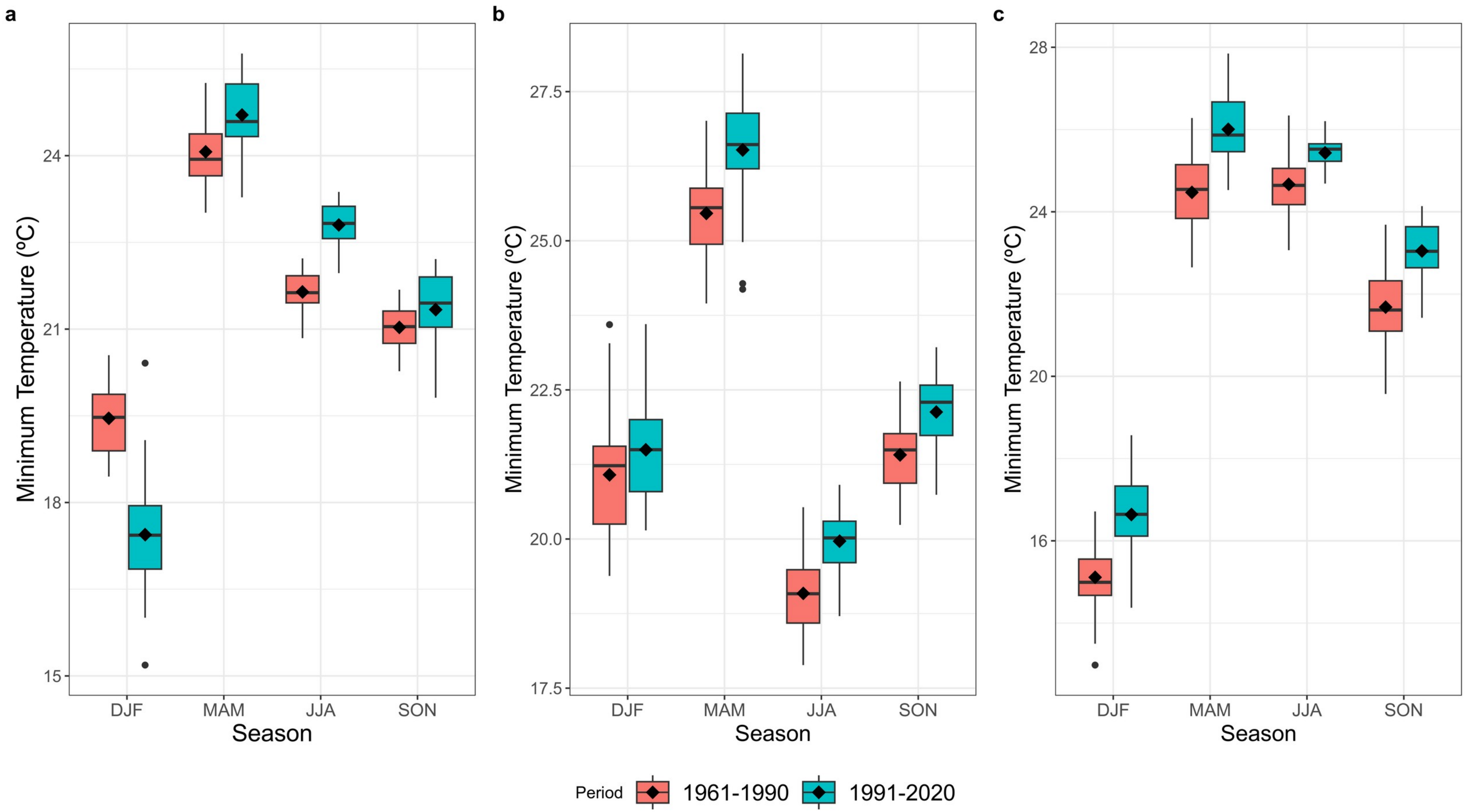


Figure 3.5: Seasonal minimum temperature (ºC) over the periods 1961-1990 and 1991-2020 in Sudan (a), Sudan-Sahel (b) and Sahel (c) zones. Legend : DJF (December-January-February); MAM (March-April-May); JJA (June-July-August); SON (September-October-November). Source: Author's Own computation, 2023.

### 3.3.5 Trends of climate extremes indices in the study area (1961 to 2020)

#### 3.3.5.1 Trends in rainfall climate extremes

The drought index indicating water availability in a year for crops use significantly increases in the Sahel zone (SPEI) and the Sudan zone (SPEI, SPI). The trend was insignificant in the Sudan-Sahel zone (Figure 3.12 and Supplementary materials, Appendix 1). Moreover, no clear trend was observed in the annual rainfall pattern over 1961-2020 (Figure 3.12). However, a significant increasing trend was observed between 1984 and 2020 in the zones except in the Sudan zone ($p<0.05$) (Supplementary materials, Appendix 1, plots d, e and f). This implies a re-wetting trend in the Sahel and Sudan-Sahel zones of Burkina Faso over the last three decades corroborating rain resumption and the Sahel greening hypothesis since the 1980s and 1990s (Alexander et al., 2006; Biasutti, 2019; Bichet and Diedhiou, 2018; Dai et al., 2004; Dardel et al., 2014; Heubes et al., 2013; Lodoun et al., 2013; Mahé and Paturel, 2009; Nicholson, 2005; Sylla et al., 2016b). Contrary to these findings, De Longueville et al. (2016) pointed out the decrease in total rainfall as the most significant change in all climatic zones of Burkina Faso until 2013. This difference could be due to the differences in the range of time series climate data studied.

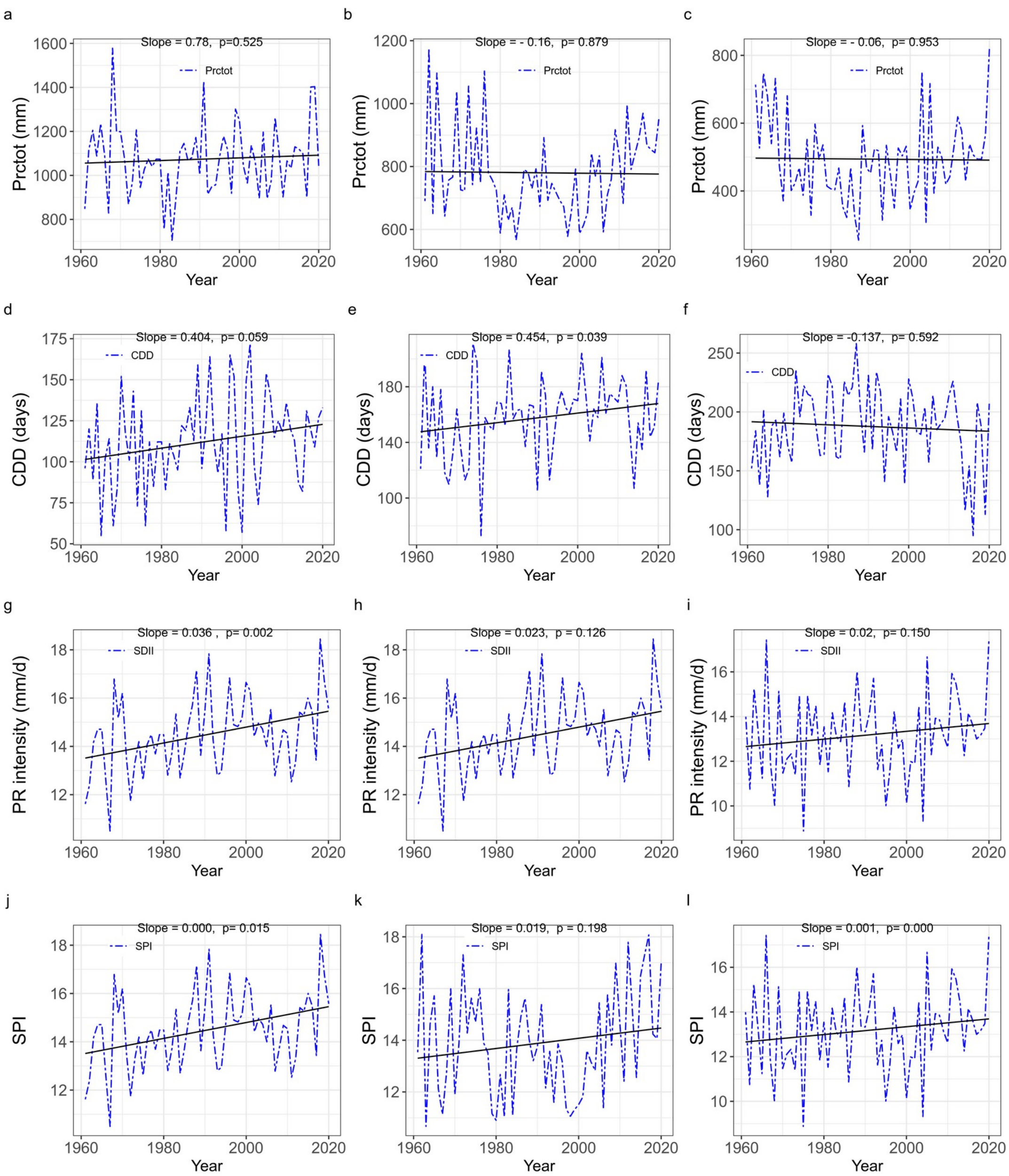


Figure 3.6: Trend in the annual rainfall and wet indices in Sudan (a, d, g, j), Sudan-Sahel (b, e, h, k ) and Sahel (c, f, i, l) zones of Burkina Faso over the period 1961-2020. Source: Author's Own computation, 2023.

#### 3.3.5.2 Trends in temperature climate extremes

Generally, the climate extremes indices revealed a warming trend throughout the Sahel and Sudan-Sahel climatic zones from 1961 to 2020 (Figures 3.13 and 3.14). Cold extremes indices (CSDI, TX10p, TN10p) showed decreasing trend, while their counterparts hot extremes (TXx, TNx, WSDI, TX90p, TN90p) revealed an increasing trend across all the studied zones ($p<0.05$). Furthermore, the coldest night (TNn) and coldest day (TXn) temperature generally showed a warming trend in all zones, indicating a reduction in the intensity of cold nights and days in the country. Our findings suggest an overall warming trend in Burkina Faso, as reported by several studies conducted in West Africa (Barry et al., 2018; Kima et al., 2015; Ly et al., 2013; NAP, 2015; New et al., 2006). Ly et al. (2013) reported a warming trend throughout West Africa from 1961 to 2010, with more frequent warm days and warm spells. According to Barry et al. (2018), warm days and warm nights have become more frequent in Burkina Faso during 1960-2010 and throughout Sub-Saharan Africa (Ly et al., 2013). Other authors reported a warming trend of both days and nights between 1961-2000 in West Africa (New et al., 2006) and South Africa (Kruger and Sekele, 2012).

Nevertheless, an increasing trend of both cold and hot nights was observed in the Sudan climatic zone. The number of normal nights is continuously converted into both extremes hot or cold nights, implying a lack of a clear pattern in the trend of night extremes (night cooling or warming) as clearly observed (night warming) in the Sudan-Sahel and the Sahel zone ($p < 0.05$). This trend was consistent with that of the diurnal temperature range (DTR), which showed no significant trend in the Sudan climatic zone but significantly increased in the Sahel and Sudan-Sahel zones. Our findings in the Sudan zone disagree with previous studies on climate extremes within West African regions (Barry et al., 2018; Ly et al., 2013; New et al., 2006) and highlight the accuracy of climate trend-related studies at the local scales.

These results suggest more changes in climate conditions across the Sahel and the Sudan-Sahel zones of Burkina Faso, contrary to the Sudan zone.

The Sahel and the Sudan-Sahel zones experienced longer cold spell (CSDI) between 1961-2020, while shorter cold spell characterised the Sudan zone. This finding in Sudan zone is consistent with New et al. (2006), who reported a decrease in CSDI in West Africa. The Sudan-Sahel zone, which constitutes the transition between the Sahel zone and the Sudan zone, experienced a persistence in warm period as revealed by the Warm Spell Duration Indicator (WSDI) within the study period (1961-2020). This result corroborates previous studies (Ly et al., 2013; New et al., 2006) supporting an average increase of 2.4 days per decade in West African region.

The comparison between cold and hot climate extremes revealed that hot extremes evolve much faster than the cold extremes. This finding suggests that the warm tails of the daily temperature distributions are changing faster than the cold tails.

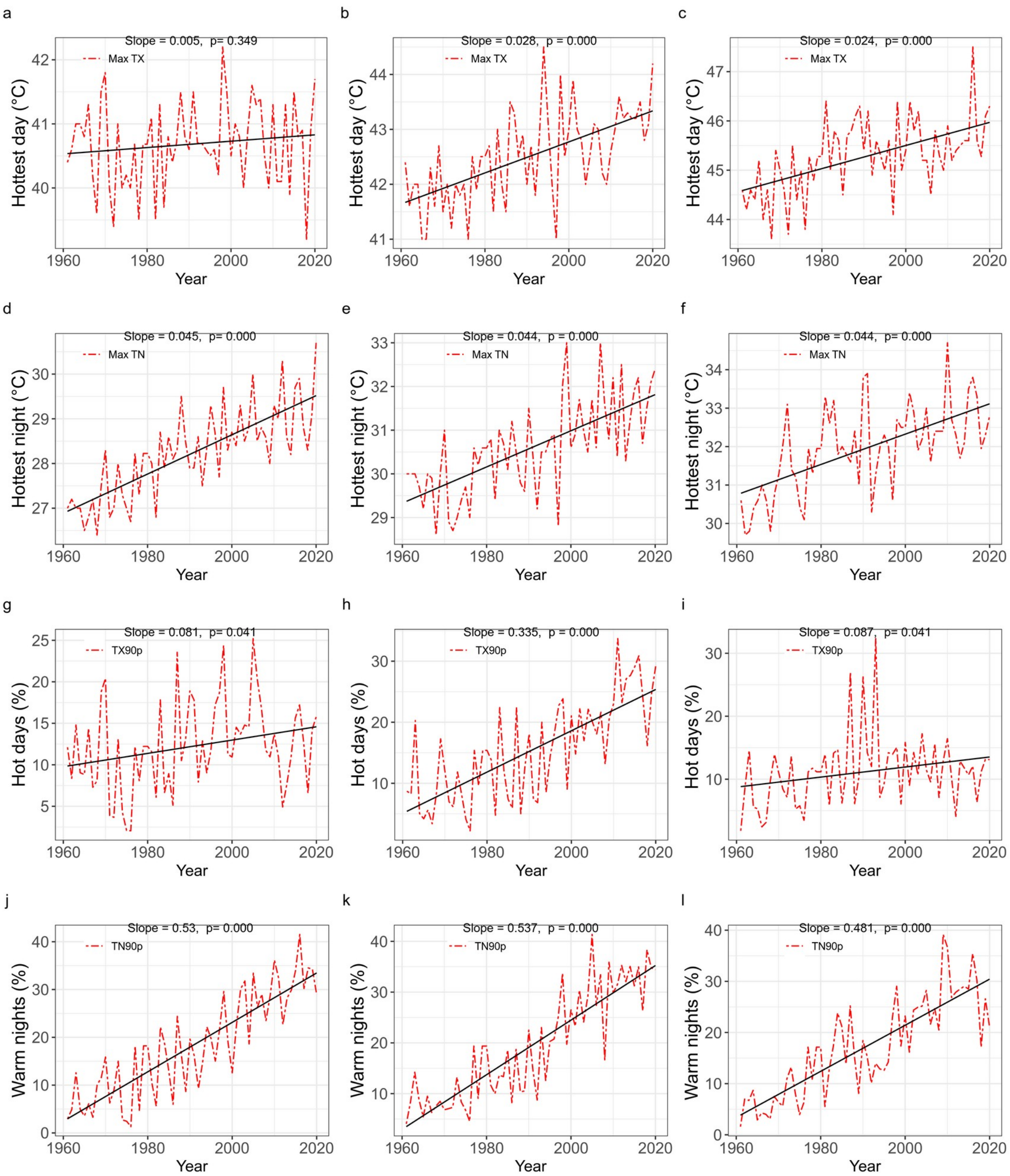


Figure 3.7: Trend in hot climate extremes in Sudan (a, d, g, j), Sudan-Sahel (b, e, h, k) and Sahel (c, f, i, l) zones of Burkina Faso over the period 1961-2020. Source: Author's Own computation, 2023.

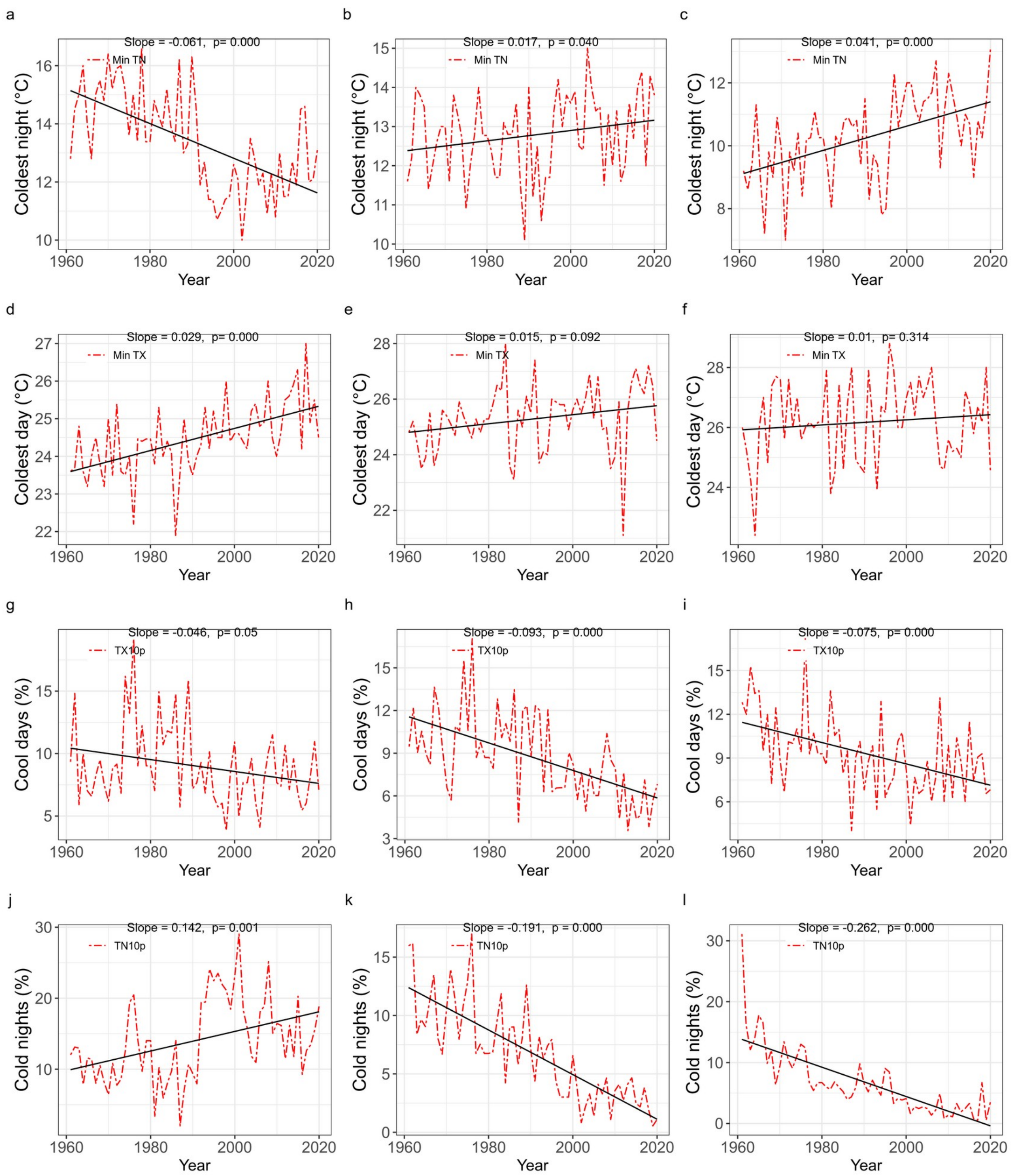


Figure 3.8: Trend in cold climate extremes in Sudan (a, d, g, j), Sudan-Sahel (b, e, h, k) and Sahel (c, f, i, l) zones of Burkina Faso over the period 1961-2020. Source: Author's Own computation, 2023.

### 3.3.6 Decadal variations in climate conditions

#### 3.3.6.1 Rainfall climate extremes

Generally, rainfall and water availability within the three zones studied revealed a high variability over five decades (2001-2010; 1991-2000; 1981-1990; 1971-1980; 1961-1970) of the 60 years (1961-2020). However, the last decade (2011-2020) was found to be the wettest of the period in all the three climatic zones (Figures 3.15, 3.16 and 3.17), ascertaining the resumption of rains observed in the recent years over the Sahel region of West Africa (Mahé and Paturel, 2009; Nicholson, 2005; Nouaceur and Muraresc u, 2020; Salack et al., 2015; Sylla et al., 2016b) and at global scale (Alexander et al., 2006).

In the Sudan zone of the country, 2011-2020 period was the wettest while the decade 1961-1970 was the rainiest (1138.9 mm). The 1981-1990 period was the driest and had the lowest annual rainfall amount (995.71mm) of the study period (Figure 3.15).

In the Sudan-Sahel zone, 2011-2020 period was the wettest (SPI=0.5, SPEI=0.6, PRCPTOT=868.7 mm/y) with the highest daily precipitation intensity, highest number of heavy rainy days and highest number of very heavy rainy days. Despite the extremely heavy daily rain (261.3 mm/d) on the 1st of September 2009 in the zone, 2001-2010 was not the wettest decade of the study period. The period 2001-2010 recorded the longest dry-spell. This implies that a good temporal distribution in rainfall events is a determinant for having a wet season or year, which is important for the growing season. The decade 1991-2000 experienced the lowest daily precipitation intensity and the lowest number of very heavy rain days. The period

1981-1990 was the driest decade followed by 1991-2000 in the study period (Figure 3.16, and Table 3.5).

In the Sahel zone, 2011-2020 was the wettest (SPI=1.5), although its recorded total precipitation (563.8mm/y) was not the highest in the study period. The driest decade was 1981-1990 (SPI=-0.5, PRCPTOT=411 mm/year) and recorded the longest dry-spell (Figure 3.17). The driest conditions can be explained by the consecutive three years drought (1982-1984) that occurred in the Sahel countries within the same period. This drought was more acute than that of 1972-1973. Furthermore, the period 1981-1990 falls within the drought extreme period (1977-1990) recorded in Burkina Faso according to Nouaceur and Muraresc u (2020).

#### 3.3.6.2 Temperature climate extremes

From the results of the Principal Component Analysis (PCA), we found all six (6) decades to be significant ($p<0.05$) in Sudan (68.38 % of total inertia against a reference of 65 %), Sudan-Sahel (87.22 % of total inertia against a reference of 64.98 %) and Sahel (87.46 % of total inertia against a reference of 70.3 %) climatic zones of Burkina Faso. The reference value is the 0.95-quantile of the inertia percentages distribution obtained by simulating 2635 (Sudan), 2636 (Sudan-Sahel) and 2641 (Sahel zones) data tables (of equivalent size based on a normal distribution).

The PCA revealed different patterns of climate conditions within the study area over the last six decades for both rainfall and temperature with the Sahel and the Sudan-Sahel being the most vulnerable to climate change compared to the Sudan zone.

Generally, the last three decades (1991-2000; 2001-2010; 2011-2020) distinguished themselves by hot climate extremes from the first three decades (1961-1970; 1971-

1980; 1981-1990) that were mainly characterized by cold climate extremes in all the three climatic zones. This aligns with previous research findings (Alexander et al., 2006; Brown and Crawford, 2008; Donat et al., 2013; Field et al., 2012; Panda et al., 2014). In the Sudan zone, 2011-2020 distinguished itself as the warmest decade (28.0 °C) with the hottest night (29.26 °C) of 1961-2020. While the decade 2001-2010 was characterised by the highest frequencies of warm nights (28.0 %) and hot days (15.6%). Hottest day (25.4°C) and highest frequency of cold nights (20.2 %) were observed during the decade 1991-2000. The coldest day (23.9°C) was observed between 1961-1970 and 1981-1990. Finally, the decade 1971-1980 distinguished itself as the coldest decade (27.4 °C) and with the highest frequency of cool days (12.2 %) (Figure 3.15 and Table 3.5).

In the Sudan-Sahel zone, 2011-2020 was the warmest (29.38°C) decade characterised by the hottest night (31.52°C), the longest duration of tropical nights (280 days), warmest day (43.31°C) and longest warm spell (27.3 days). The period 2001-2010 was the second decade in terms of persistence of warm spell, coldest night and tropical nights duration. In addition, 2001-2010 distinguishes itself by the highest frequency of warm nights (29.2 %) and hot days (19.3 %) of the study period (1961-2020) (Figure 3.16 and Table 3.5). The period 1991-2000 was the third warmest decade (28.7°C) and 1981-1990 revealed, on average, the coldest night (12.37 °C). The 1971-1980 period was the coldest (28.0°C) and experienced high cold spell duration (4.7 days), while the period 1961-1970 was characterised by the coldest day (24.61 °C).

In the Sahel zone, 2011-2020 was the warmest decade (30.2°C) and distinguished itself by the hottest day (45.9 °C) and night (32.7°C), the highest frequency of warm nights (28.2 %) and tropical nights duration (264.1 days). The period 2001-2010 was the second warmest decade (30.17°C), while 1991-2000 was the third warmest (29.8°C) and revealed the highest frequency of hot days (14 %). The period 1981-1990 recorded the coldest day (25.7 °C) of the study period (1961-2020). Both 1961-1970 and 1971-1980 periods showed the coldest night (9.4 °C), while only 1961-1970 was characterised by the highest frequency of cool days (11.7 %) and cold nights (14.5 %) (Figure 3.17 and Table 3.5).

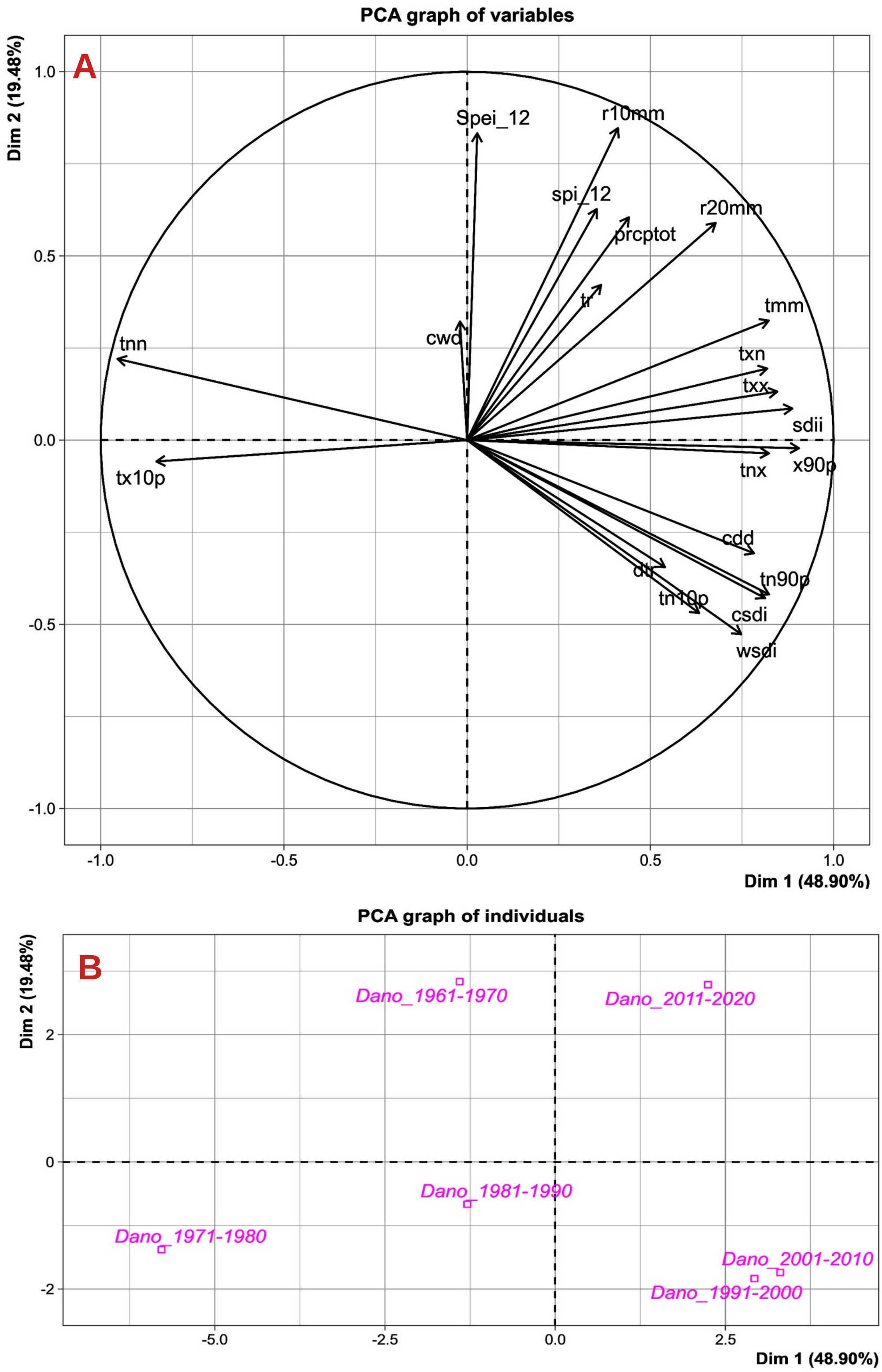


Figure 3.9: Decadal trend of rainfall and temperature indices within the Sudan zone (Dano). (A ) Graph of Variables; (B) Graph of individuals. The component 1 explained 48.9 % of the variables and summarise the temperature variables. The component2 explains 19.5 % of the variables and identifies itself to rainfall availability. Source: Author's Own computation, 2023.

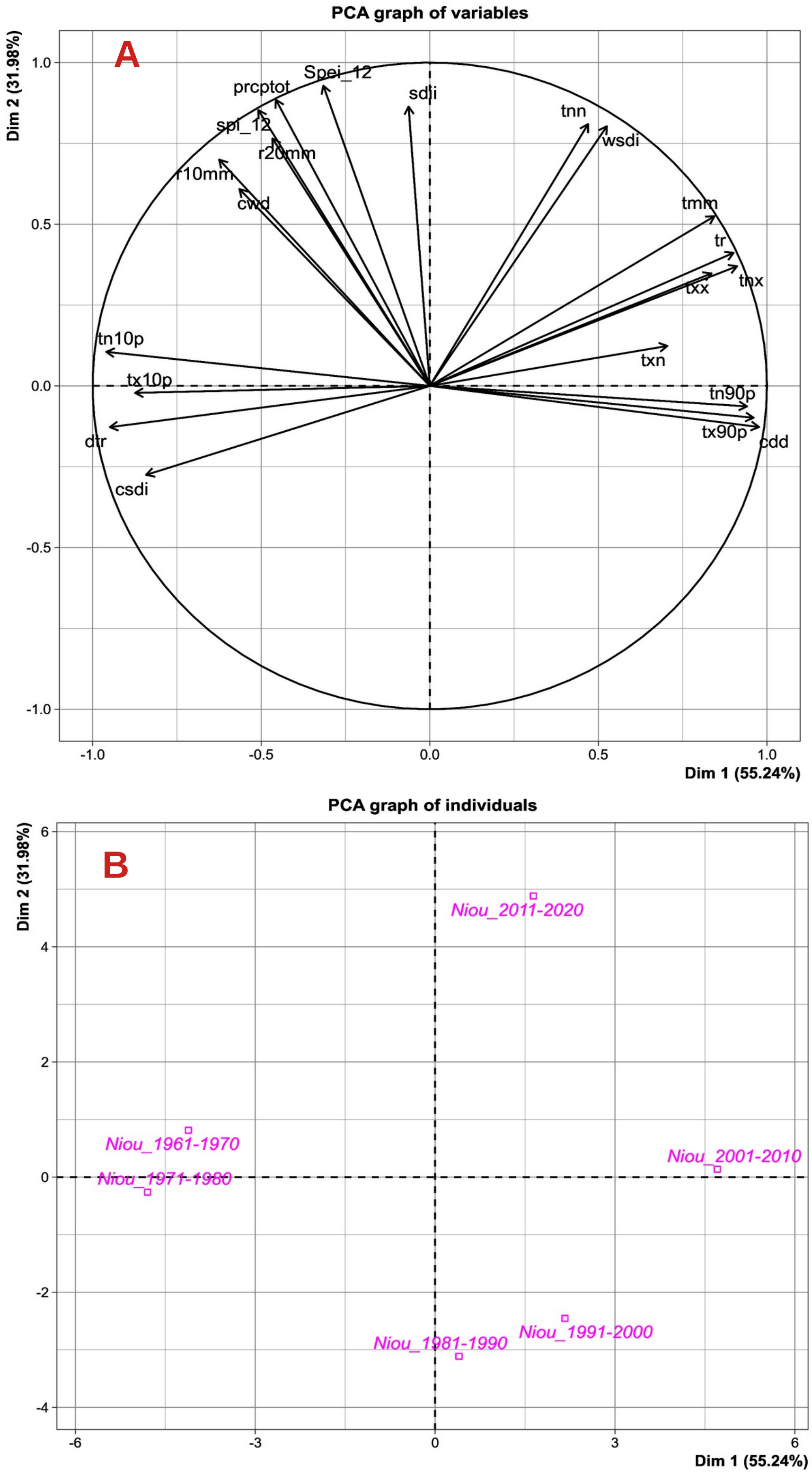


Figure 3.10: Decadal trend of rainfall and temperature indices within the Sudan-Sahel zone (Niou). (A ) Graph of Variables; (B) Graph of individuals. The component 1 explained 55.2 % of the variables and summarise the temperature variables. The component 2 explains 32.0 % of the variables and identifies itself to rainfall availability. Source: Author's Own computation, 2023.

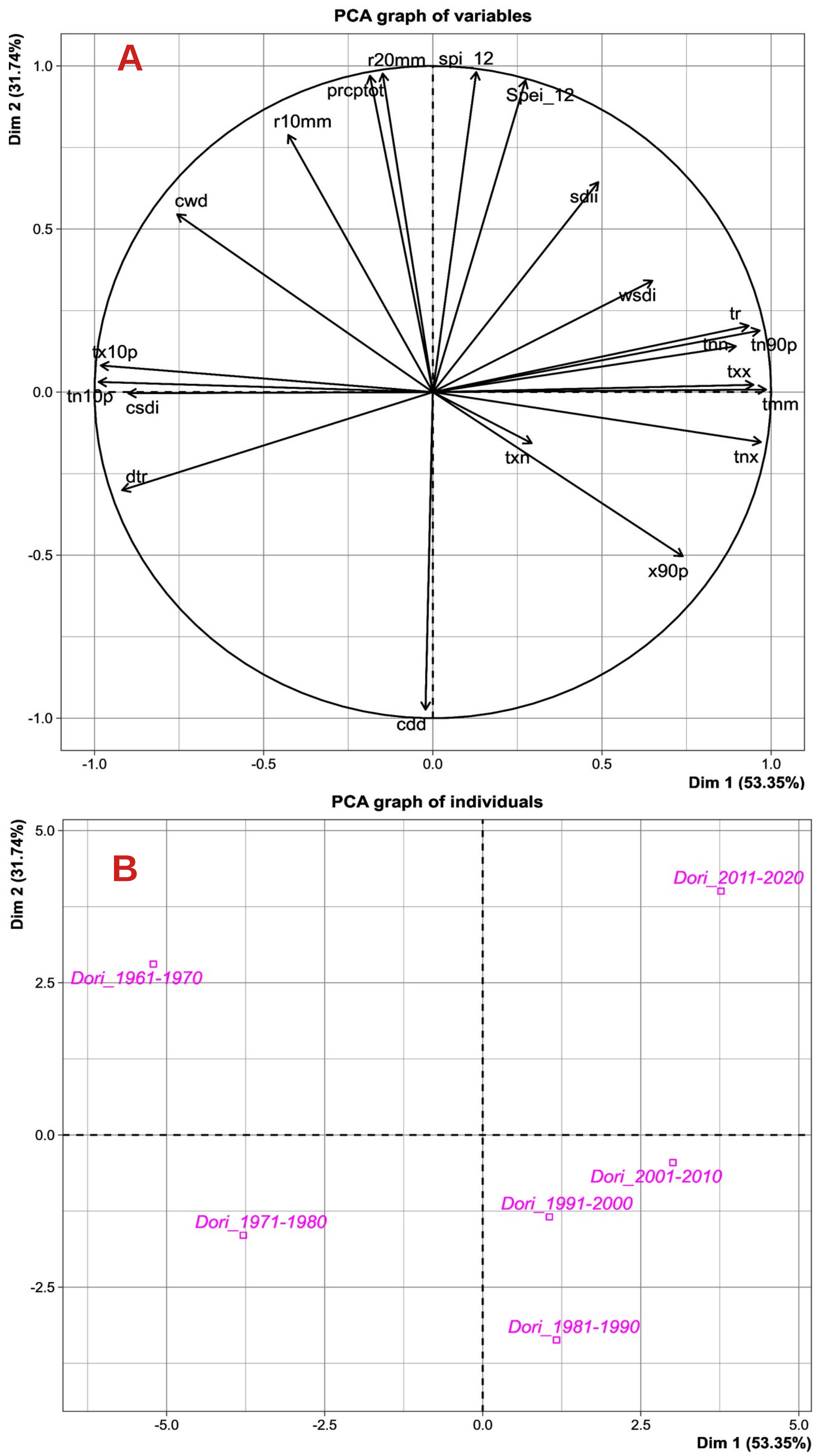


Figure 3.11: Decadal trend of rainfall and temperature indices within the Sahel zone (Dori). (A ) Graph of Variables; (B) Graph of individuals. The component 1 explained 53.4 % of the variables and summarise the temperature variables. The component 2 explains 31.7 % of the variables and identifies itself to rainfall availability. Source: Author’s Own computation, 2023.

Table 3.5: Temperature-related information within each climatic zone and over six decades of the period 1961-2020

| Decades | 1961-1970 | 1971-1980 | 1981-1990 | 1991-2000 | 2001-2010 | 2011-2020 |
|---|---|---|---|---|---|---|
| Sudan zone | coldest day (23.9 °C) | coldest decade (27.4 °C)<br><br>highest frequency of cool days (12.2 %) | coldest day (23.9 °C) | hottest day (25.4°C)<br><br>highest frequency of cold nights (20.2 %) | coldest night (11.81°C)<br><br>highest frequency of warm nights (28.0 %)<br><br>highest frequency of hot days (15.6 %) | warmest decade (28.0 °C)<br><br>hottest night (29.26 °C) |
| Sudan-Sahel zone | coldest day (24.61 °C) | coldest decade (28.0°C)<br><br>highest frequency of cool days (11.4 %)<br><br>highest frequency of cold nights (11.7 %) | coldest night (12.37 °C) | third warmest decade (28.7°C) | highest frequency of hot days (19.3 %)<br><br>highest frequency of warm nights (29.17 %) | warmest decade (29.38°C)<br><br>hottest day (43.31 °C)<br><br>hottest night (31.52 °C) |
| Sahel zone | coldest decade (28.8°C)<br><br>coldest night (9.4 °C)<br><br>highest frequency of cool days (11.7 %) | coldest night (9.4 °C) | coldest day (25.71 °C) | highest frequency of hot days (14 %) | second warmest decade (30.17°C) | warmest decade (30.2°C)<br><br>hottest day (45.9 °C)<br><br>hottest night (32.7 °C)<br><br>highest frequency |

| | | |
|---|---|---|
| | highest frequency of cold nights (14.5 %) | of warm nights (28.2 %) |

*Pink colour characterise hot climate extremes and Green colour characterise cold climate extremes. Source: Author's Own computation, 2023.

### 3.4 Conclusion

The current study found evidences of change and variability in rainfall and temperature patterns in the study areas. However, the change is much more pronounced in temperature than in rainfall, whatever the scale of analysis. Moreover, the study revealed globally that extreme hot indices are evolving much faster than their counterpart cold extremes within the study zones. This observation suggests a clear pattern of climate warming across the three agroclimatic zones studied in the current research work.

Decadal climate indices analysis showed that the last three decades in each climatic zone distinguished themselves by hot climate extremes from the first three decades that were globally characterized by cold climate extremes. Likewise, in general, recent decades revealed to be the wetter of the period 1961-2020.

The warming climate and high rainfall variability experienced within the study zones constitutes more stresses for both livestock and crop production activities, thereby threatening the livelihoods of farming households in such zones. The induced threats may consist of crop yield reduction and livestock disease occurrence. However, the Sudan-Sahel and Sahel zones, where climate change was more pronounced, are likewise more exposed to such threats.

# CHAPTER 4: INFLUENCE OF CLIMATE CHANGE ON CROPS PRODUCTIONS AND LIVESTOCKS' DISEASES OCCURRENCE IN BURKINA FASO

## ABSTRACT

West African Sahel is one of the most vulnerable regions globally to climate change which negatively affects human and the ecological systems. Understanding past climate and impacts in the Sahel region is fundamental to climate change adaptation and mitigation. This study examines the impacts of climate extremes on five major crops (maize, millet, sorghum, groundnut, cowpea) and five livestock diseases of economic importance. Pearson's correlation test, multiple linear regression analysis and Poisson regression analysis were used to assess climate influence on crop yield and occurrence of livestock diseases. The results showed a significant association between crop yield, occurrence of livestock diseases and climate extremes. These extremes explained between 23.0 to 50.2 % of the variations in crop yield. Cold days and nights, coldest day and night, dry spells, and daily warming adversely affected crop yields at least within one of the climatic zones. Overall, warm and wet conditions saw resurgence of livestock diseases across zones. Within the Sudan zone day warming favoured ($p<0.001$) the occurrence of Pasteurellosis of small ruminants (PSR) (increased cases by 1.5-1.7 units); cool night favoured Foot-and-mouth disease (FMD) (increased cases by 1 unit) and Contagious bovine pleuropneumonia (CBPP) (increase cases by 1.3 units). In the Sudan-Sahel zone the wet spell induces the resurgence of FMD (increase cases by 2.6 units). Night warming and day cooling were observed to favourably increase the occurrence of the Lumpy Skin Disease

(LSD) (increased cases by 1.1-9.4 units); while day warming and wet spell also favourably increased the occurrence of the PSR (increased cases by 1.1-1.4 units) and Newcastle (increased cases by 1.3-3.2 units). In the Sahel zone, night warming and rain event significantly induced the resurgence of FMD (increased cases by 1.1-1.3 units), PSR (increased cases by 1.0-1.2 units), LSD (increased cases by 1.1 and 2.8 units) and Newcastle (increased cases by 1.1 units). To address the adverse effects of climate change on crop and livestock productions, a climate-smart policy promoting drought-tolerant breeds, drought-resistant and short-duration varieties that can adapt to extreme climate conditions is recommended. Above all, adopting practices such as crop-livestock integration can help mitigate and/or adapt to the impacts of climate change and non-climatic factors on the agro-pastoral sector in Burkina Faso.

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**Key words:** Climate change, Food security, livestock diseases, West African Sahel.

## 4.1 Introduction

Global climate change constitutes an important challenge with negative impacts on natural and human systems in recent decades on all continents and across oceans as well (IPCC, 2014c). More specifically, the changing climate have negative impacts on agricultural systems and food security worldwide (IPCC, 2001b; Vogel et al., 2019; Zhu and Troy, 2018) and these negative impacts are likely to persist and even worsen in the future (Mustapha and Arshad, 2014; Salack et al., 2015). Indeed, within many parts of the world, global warming and rapid changes in climatic conditions are predicted to affect cereal cropping with significant reduction in productivity (Butt et al., 2005; Chadalavada et al., 2021; Nelson et al., 2018, p. 200; Schlenker and Lobell, 2010). That pose a risk to global food security if adequate measures are not adopted worldwide. Future crop productivity has received a growing attention because of the expected threats of climate change on global food security (Ash et al., 2007; Gaiser et al., 2011; Gourdji et al., 2013; Hansen, 2005; Hansen and Sivakumar, 2006; Meza et al., 2008; Mustapha and Arshad, 2014). The altered climate conditions in West Africa, have induced regional average yield declines by 10-20% for millet and 5-15% for sorghum (El Bilali, 2021; Sultan et al., 2019b). Production loss also implies the loss of income for farmers and revenues for countries (El Bilali, 2021), which accounted for 2.33-4.02 billion USD for millet and 0.73-2.17 billion USD for sorghum between 2000 and 2009 (Sultan et al., 2019). Mono systems of crop and livestock farming, particularly under dry-land conditions in arid and semi-arid regions, have been highly impacted by climate deterioration (Hassan, 2010). This high vulnerability is mainly due to the fact that this region's agricultural systems are predominantly rain-fed (Hassan, 2010; Sanfo et al., 2017). Inappropriate or poor adoption of mixed cropping in the region gives room to such vulnerability and low resilience. In fact, the mixed systems can help farmers to adapt to the impacts of climate change in many ways, including increased efficiencies of production that sometimes provide important mitigation co-benefits as well (Thornton and Herrero, 2014).

Cropping systems in the region, particularly Burkina Faso, is predominantly subsistence-oriented with small holdings characterised by small farm size and highly variable herd size and composition. Cereal crops such as sorghum *(Sorghum bicolor*), millet *(Panicum sp.*) and maize (*Zea mays L.*) constitute the main pillars of Burkina

Faso's food security and across West Africa (Waongo et al., 2015). Besides cereal crops groundnut (*Arachis hypogaea)* and cowpea (*Vigna unguiculata*) play a double role of staple and cash crop for vulnerable small farmers all over the country. Along-with crop farming, cattle, sheep and goats are the most important livestock species, kept by most farmers across the climatic zones (Zampaligré et al., 2014).

In the last decades, a growing literature has been paid on climate change and variability in West African Sahel (Daron and Stainforth, 2014; Kima et al., 2015; Kotir, 2011; Lodoun et al., 2013; Padgham et al., 2015; Sylla et al., 2016b; USAID, 2012; West et al., 2008; Zampaligré et al., 2014). Some authors revealed that agro-pastoral production was adversely affected by climate change through the reduction in grazing area and forage availability and quality, in milk and meat production, herd size, crop yields, livestock fertility etc. (Kima et al., 2015; Sanou et al., 2018; Zampaligré et al., 2014). On the contrary, it was found an increased crop pests, animal diseases and mortality (Kima et al., 2015; Sanou et al., 2018; Zampaligré et al., 2014). The majority of findings were based on farmers' perceptions and impacts simulations from models (Ash et al., 2007; Gaiser et al., 2011; Gourdji et al., 2013; Hansen, 2005; Kima et al., 2015; Meza et al., 2008; Mustapha and Arshad, 2014; Sanou et al., 2018; Zampaligré et al., 2014). The analysis of climate change at a wider temporal scale and its effects on crop and livestock production are limited by the lack of long-term climate records in most Sahel countries. This explains the insufficient updated information on crop sensitivity and livestock susceptibility to climate change. However, they are at the heart of the farming systems of the majority of small farmers allover the West Africa Sahel countries and Burkina Faso in particular. Much more, there is limited updated information on the interrelation between climate extremes indices and crop yield (Panda et al., 2014; Vogel et al., 2019) and livestock diseases (Crawford et al., 2016; Fafa et al., 2018a, 2018b).

The knowledge gaps prevent the development of appropriate policy intervention in addressing climate change effects on agricultural systems. To address them, this study sought to perform a more detailed investigation of climate conditions and its implications within the Sahel, Sudan-Sahel and Sudan zones of Burkina Faso using climate indices. Indeed, there is still much to be understood about the food safety implications of climate change and variability in Burkina Faso.

We hypothesized that changes in climate patterns across the climatic zones of Burkina Faso have positively influenced agro-pastoral productions.

Current research aims to analyze the influence of climate extreme indices on the yield of major crops and common livestock diseases across three climatic zones of Burkina Faso.

## 4.2 Study Methods

### 4.2.1 Study area

The study area comprises three provinces distributed along the three climatic zones of Burkina Faso. This study sites were Seno (13°32'13.2"N – 14°28'12"N and 0°37'30"W – 0°32'60"E) in the Sahel zone, Kourweogo (12°17'24"N – 12°54'18"N and 2°4'55.2" – 1°35'42"W) in the Sudan-Sahel zone, and Ioba (10°42'7.2"N – 12°54'18"N and 3°26'56.4" – 2°36'39.6"W) in the Sudan zone (Figure 4.1). The climate is tropical sub-arid to sub-humid with a unimodal rainfall regime. The study sites are aligned along a climatic gradient characterized by a North to South increase in mean annual rainfall (300 - 1200 $mm.year^{-1}$) and a decrease in mean annual temperature (35°C to 20°C). Cropping and/or livestock rearing constitute the main socio-economic activities as we move from the Sahel to the Sudan zone.

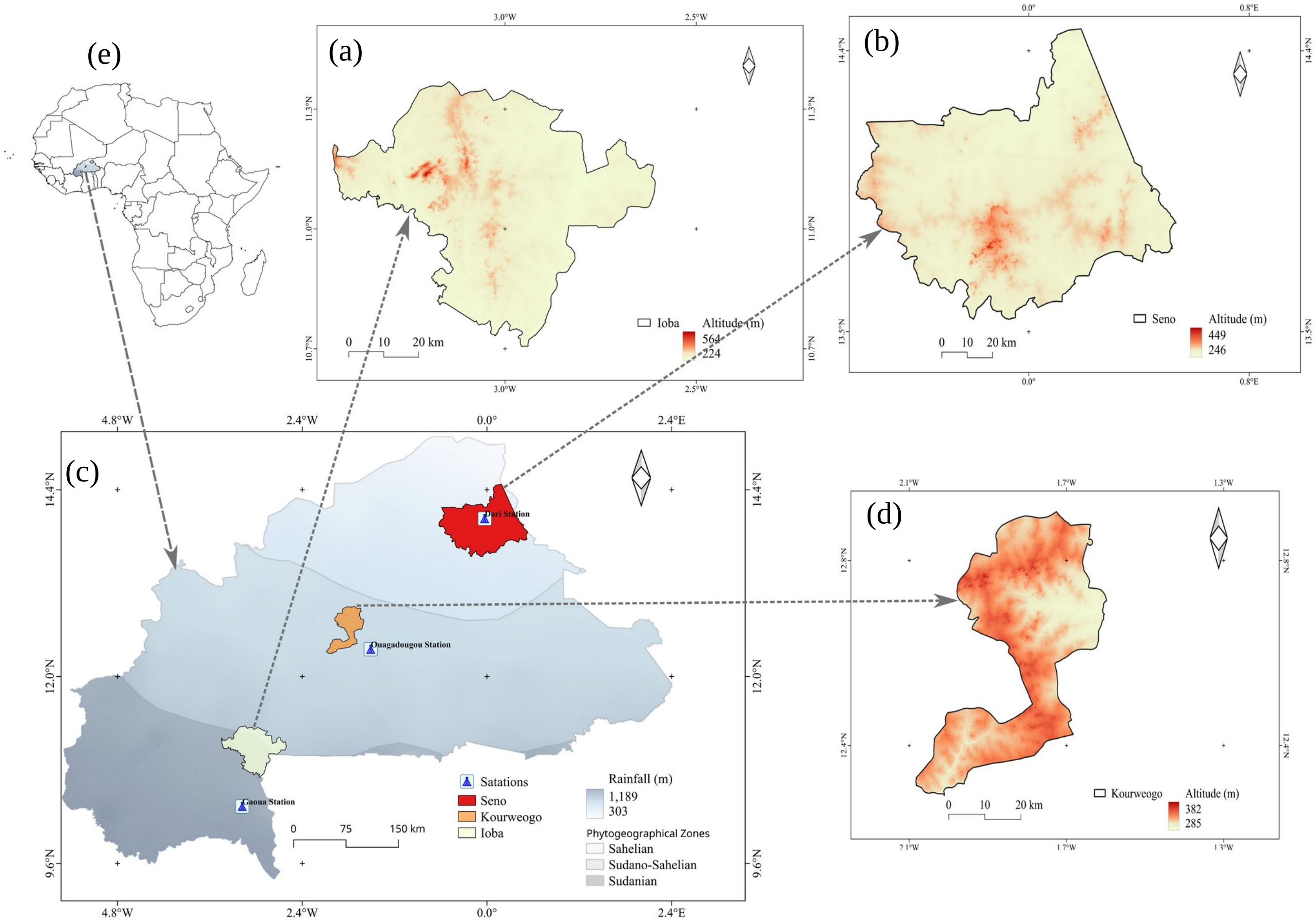


Figure 4.1: Location of the study provinces across climatic zones of Burkina Faso. (a) Province of Ioba; (b) Province of Seno; (c) Map of Burkina Faso; (d) Province of Kourweogo; (e) Map of Africa (Source: Sanou, 2023).

### 4.2.2 Data collection

#### 4.2.2.1 Crop production data

Five major crops were considered in this study, including maize, millet (*Panicum sp.*), sorghum (*Sorghum bicolor)*, cowpea (*Vigna unguiculata)*, and groundnut (*Arachis hypogaea*). Maize (*Zea mays L.)*, millet and sorghum represent staple crops and greatly contribute to food security in West African region (Waongo et al., 2015). Cowpea and groundnut are cash crops and source of incomes for small farmers. In each climatic zone, we collected data on annual yields (kg/ha) of the five crops from 1984 to 2020. The data cover three provinces: Seno in the Sahel zone, Kourweogo in Sudan-Sahel zone and Ioba in the Sahel zone. The data was obtained from the Ministry of Agriculture. The average climatic requirements and resilience capacity of the studied crops under arid and semi-arid climatic conditions are presented in Table 4.1.

**Table 4.1**. Crops growth climatic exigences and their resilience capacity to extremes climate conditions

| Crops species | Range of required average temperature (°C) and rainfall (mm/y) | Resilience capacity | Sources |
|---|---|---|---|
| Maize | 18 – 34ºC<br>250–5000 mm/y | Tolerance to brief exposures to extreme temperatures (< 0 °C and > 40 °C) | (Hatfield et al., 2011; Seetharam et al., 2021; Vâtcă et al., 2021) |
| Millet | 26 – 30 °C;<br>350 – 500 mm /y | Tolerance to drought and heat stress | (Chapke et al., 2020; Mustapha and Arshad, 2014) |

| Crops species | Range of required average temperature (°C) and rainfall (mm/y) | Resilience capacity | Sources |
|---|---|---|---|
| Sorghum | 27 – 30 ºC ;<br>400 –800 mm/y | Warm-weather crop | (Du Plessis, 2008) |
| Cowpea | 28–30°C ;<br>500–1200 mm/y | Drought-tolerant varieties for sahel | (Agossou et al., 2020; Dugje et al., 2009) |
| Groundnut | 25 – 30ºC<br>300 – 1000 mm/y | Drought tolerant | (Weiss, 2000) |

#### 4.2.2.2 Livestock diseases data

Veterinary clinic records for the period 2003 – 2019 were collected from the national statistical office of the Department of Livestock Services. The data consisted of annual reported cases (i.e. number of sick animals) of common livestock diseases within the three provinces studied. Five livestock diseases of economic and health importance in Burkina Faso were studied in this research work. They were the foot-and-mouth disease (FMD); pasteurellosis of small ruminants (PSR), Newcastle disease (New); Contagious Bovine pleuropneumonia (CBPP) and Lumpy skin disease (LSD).

#### 4.2.2.3 Climate and climate extremes data

Long time series of climate records spanning sixty (60) years (1961–2020) were obtained from the National Agency of Meteorology of Burkina Faso. The dataset was collected from three weather stations across three climatic zones of Burkina Faso. The stations were Dori (Sahel zone), Ouagadougou (Sudan-Sahel zone), and Gaoua

(Sudan zone). The historical climatic data obtained were daily rainfall, daily maximum temperature and daily minimum temperature.

### 4.2.3 Data analysis

Pearson's correlation test and multiple linear regression analysis (equation 4.1) (Sese et al., 2022) were performed to assess the influence of extreme climatic conditions on the yields of the five crops. Livestock disease occurrence susceptibility to climate extremes was rather assessed using Poisson regression analysis as shown in equation 4.2 (Cupal et al., 2015). This is suitable for analyzing the relationship between count (discrete) and continuous data. This was done between the number of sick animals per year (discrete variable) and new variables derived from Principal Component Analysis of the historical climate data (15 relevant climate indices for agro-pastoral sector) as continuous variables.

$$Y_t = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + \varepsilon_o \qquad \text{equation 4.1}$$

Where, *Yt* represents the response variable (crop yield in kg/ha) given the predictors (climate variables), $X_1, X_2, X_3, \ldots, X_k$ and $\beta_0, \beta_1, \beta_2, \beta_3, \ldots \beta_k$ are coefficients of predictors and $\varepsilon_0$ represents the error terms.

$$\log(E[Y/X]) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k \qquad \text{equation 4.2}$$

Where, E[Y|X] represents the expected value of the response variable $Y$ (count of sick animals) given the predictors (climate variables), $X_1, X_2, X_3, \ldots, X_k$ and $\beta_0, \beta_1, \beta_2, \beta_3, \ldots \beta_k$ are unknown parameters to be estimated. To interpret the estimates, the Incidence Rate Ratio (IRR) was computed by exponentiating each coefficient as:

$$IRR = \exp^{(Estimated\,parameter)} \qquad \text{equation 4.3}$$

The exponentiated values of estimates was used as the actual count of the number of sick animals of each disease due to increases in predictors values. Mean temperature, total precipitation and climate extreme indicators were used as predictors. Climate data of the period 1984 - 2020 and 2003 - 2019 were used to fit with the crop yield data and livestock disease occurrence data of corresponding periods respectively.

## 4.3 Results and discussion

### 4.3.1 Influence of climate change and variability on crop production

The results suggested that climate variability and change differently influence crops production in the study area (Figures 4.2; 4.3; 4.4 and Table 4.2). Both positive and negative impacts of climate conditions on the production of the five major crops over the last three decades were identified. Each studied zone presented some specific relationship between crops yields and climate conditions leading to different sensitivity to climate.

#### 4.3.1.1 Bivariate relationship between climate extremes and crop yield across climatic zones

**(i) Sudan zone**

Cowpea yield correlated negatively with cool days and positively with amount of warm nights, daily precipitation intensity and coldest day. Millet yield showed positive association with the coldest day and warm nights but negatively associated with the coldest night ($p < 0.05$). Sorghum yield was positively correlated with warm nights while groundnut yield showed a significant negative association with tropical nights. (Figure 4.2). It appears therefore that four of the studied crops were significantly influenced by climate conditions in the zone, while maize was less affected.” This means that, despite climate change, the climatic exigences (Table 4.2) of the maize varieties grown in the zone, were not adversely disturbed.

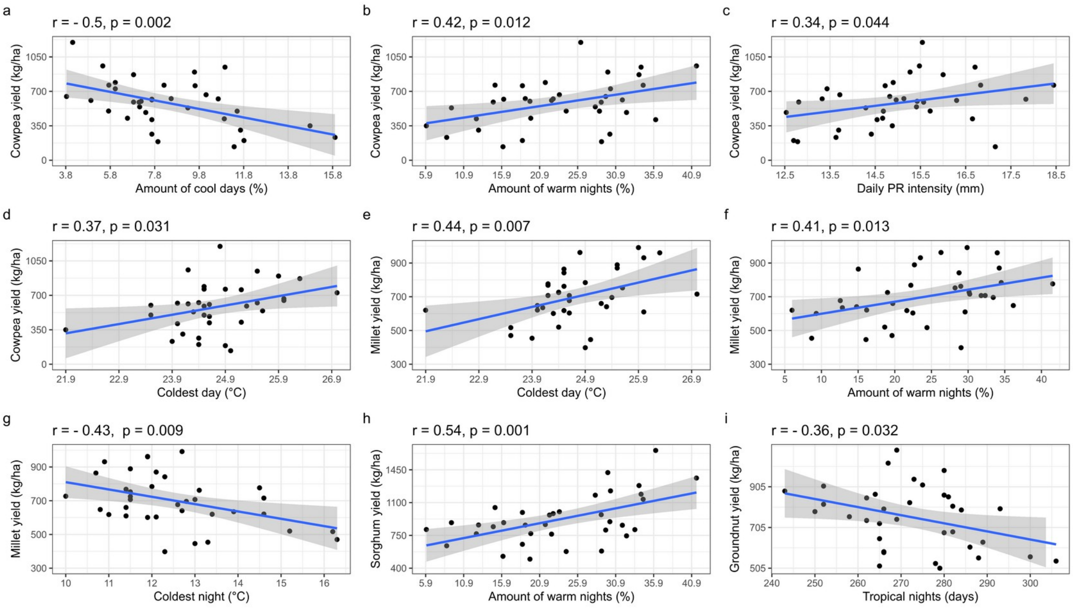


Figure 4.2: Bivariate relationship between climate indices and major staple crops yield in Sudan zone. Source: Author’s Own computation, 2023.

**(ii) Sudan-Sahel zone**

The yield of all the five studied crops were significantly associated with climate extremes indices ($p < 0.05$), meaning that their growth requirements may have been offset by these extremes in the zone (Figure 4.3). Indeed, maize yield was negatively associated with the coldest night and the consecutive dry days respectively. Groundnut yield was negatively associated with the coldest day and consecutive dry days respectively while millet yield revealed a negative and positive association with the number of heavy rain days and the coldest night respectively. Sorghum yield was found negatively and positively associated with the coldest night and hottest night respectively while the coldest night negatively associated with cowpea yield (Figure 4.3).

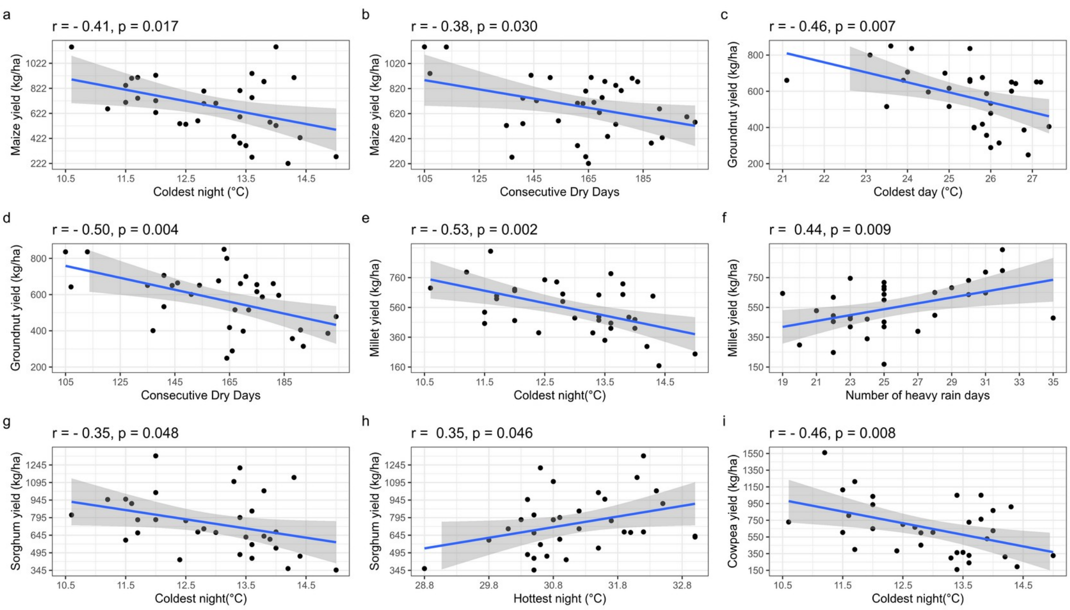


Figure 4.3: Bivariate relationship between climate indices and major crops yields in Sudan-Sahel zone. Source: Author's Own computation, 2023.

### (iii) Sahel zone

Likewise in the Sudan-Sahel, the yield of all the five studied crops were significantly associated with climate extremes indices (Figure 4.4). Maize yield correlated positively with the number of heavy rain days while groundnut also showed positive correlation with the number of very heavy rain days. Cowpea yield was rather positively associated with cold nights and the average daily minimum temperature. Sorghum also showed positive correlation with annual precipitation and the number of heavy rain days respectively. Millet yield recorded a negative correlation with cold nights but a positive association with number of heavy rain days and with the consecutive wet days (Figure 4.4). Unlike the two previous zones, all the five crops studied were in general significantly and positively associated with wet climate extremes in the Sahel zone. It implies that with regard to climate conditions, crops yield variation was more rain-dependent than temperature dependent in the Sahel zone. Nevertheless, millet and cowpea growing requirement seems to have been disturbed through nights cooling (Figure 4.4; Table 4.2).

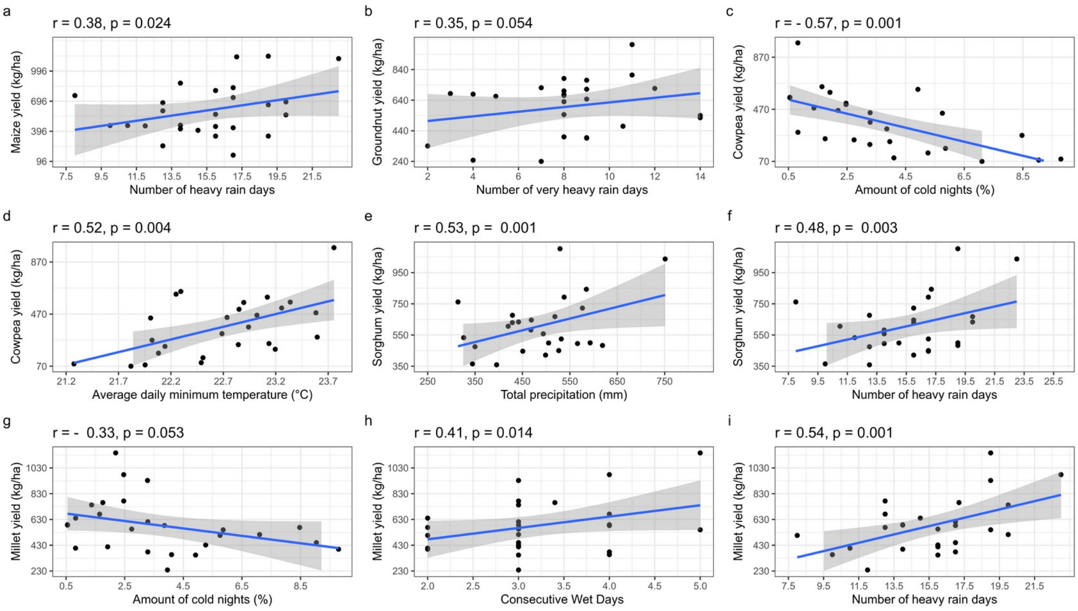

Figure 4.4: Bivariate relationship between climate indices and major staple crops yield in Sahel zone. Source: Author’s Own computation, 2023.

#### 4.3.1.2 Crops sensitivity to climate change across the climatic zones

The results suggested that climate variability and change have different directions of influence (negatively or positively) on crops production (Figure 4.2, 4.3, 4.4 and Table 4.2).

Similar findings were reported on cowpea crop yields in Nigeria during 1961-2006 (Ajetomobi and Abiodun, 2010), in Mali (Butt et al., 2005) and even worldwide (Raza et al., 2019). Furthermore, Waha et al. (2013) also reported that climate change adversely affected maize production (10% to 33% yield decrease) in Sub-Saharan Africa with positive impacts found in mountainous and cooler regions of South and East Africa (6% yield increase).

The findings revealed that some extreme climate indices have negative impacts on staple crop yields in the study area. About 67 % (14 over 23 indices) of the studied extreme climate indices significantly influenced crop yield across the three climatic zones. This result is congruent with several authors in Africa (Abubakar et al., 2020; Adisa et al., 2019; Knox and Rodríguez, 2012; Paliwal et al., 2020; Sultan et al., 2019a) and elsewhere (Chadalavada et al., 2021).

The negative impacts consist of a severe disruption in plant development through several morphological, physiological, biochemical, and molecular changes leading to yield decline (Chadalavada et al., 2021; Raza et al., 2019).

Crop production in the Sudan and Sahel zones were influenced by six climate indices, while five climate indices affected crop yield in the Sudan-Sahel zone.

Generally, the study found that the climate indices explained one quarter to half of the variability in crop yields (maize, groundnut, cowpea, sorghum and millet) across the study areas. The following sections gives more detailed information on specific sensitivity of crops yield to climate extremes by climatic zones.

**(i) Sudan zone**

Climate indices that were unfavourable to crops yields were the cool days (TX10p), average daily temperature (TMm), the coldest night (TNn) and consecutive dry days (CDD) affecting cowpea, sorghum and millet yield. A one unit increase in cool days could reduce cowpea yield by 58.4 kg/ha while one degree increase in the daily average temperature (TMm) could reduce sorghum yield by 391.2 kg/ha. The coldest night (TNn) may cause 45.6 kg/ha reduction in millet yield. Millet yield could also decrease by 1.6 kg/ha for one day increase in consecutive dry days (CDD). Crop failure due to climate dry conditions is highlighted from previous findings (Abubakar et al., 2020; Adisa et al., 2019). Beside the adverse impacts of dry spells, our results also indicated that a unit increase in warm nights (TN90p) could increase sorghum yields by 24.6 kg/ha. Heavy rain days (R10mm) could have been favourable to both millet and cowpea production in the Sudan zone. A one day increase in the heavy rain days could have increased millet and cowpea yield by 5.5 and 11.8 kg/ha, respectively, while a degree warming of the coldest day (TXn) could cause an increase in millet yield by 97.7 kg/ha.

The average temperature and rainfall over the study period (1984-2020), was in the range of that is required for crops optimal growth (Table 4.2; Appendix 2). However, yields were significantly affected by extreme climate conditions. This means that climate extremes (cold days, coldest day and night, warm nights, heavy rain days and dry spell) more than average climate conditions are responsible for observed variation of crop yields in the zone. Moreover, as indicated by Vogel et al. (2019) temperature-related extremes show a stronger association with yield anomalies than precipitation-related extremes. Climate extremes in this zone explained a variation of 23 – 47.7 % of crop yield. This underlines the fact that 52.3 – 77% of the variation in Sudan zone crop yield, may be attributed to non-climatic factors such as improved seed, fertility of the soils, and farming methods, among others as indicated by Atiah et al. (2021) who suggested in their research a need to study the impacts of non-climatic factors on maize yield to maximize its production in the country. This susggestion is paramount for Burkina Faso and SSA agriculture sector as well.

**(ii) Sudan-Sahel zone**

Results of three fitted multiple linear regression models revealed that maize, groundnut and millet yields were significantly affected by coldest night (TNn), cold spell duration indicator (CSDI), coldest day (TXn), consecutive dry days (CDD), and heavy rain days (R10mm). TNn and CSDI could have impacted maize yield differently (Table 4.2). A degree increase in the coldest night (TNn) could have induced maize yield decline by 83.8 kg/ha while a day increase in the cold spell duration could have induced maize yield increase by 50.7 kg/ha. Groundnut production in the zone could have experienced yield decline by 57.7 and 3.4 kg/kg due to a degree and a day increases in the coldest day and dry spell respectively. Millet yield was significantly but differently influenced by TNn and R10mm. While millet yield could decline by 77.6 kg/ha due to a degree increase of the coldest night, it could rather increase by 17.8 kg/ha in response to a day increase in the number of heavy rain days. The decline in crop yields within Sudan-Sahel, could be due to warming trend of climate conditions such as the increasing trend of cold extremes (TNn, TXn). Inversely, the cooling trend and the increase in the heavy rain days could have induced the observed yield increases. It seems that both nights and days cooling are favourable to maize production as water losses through evapotranspiration are reduced:

The warming trend in the zone might have offset the observed favourable effect of rain on crop yields (Panda et al., 2014; Sultan et al., 2019b, 2019a; Wheeler et al., 2000). The findings related to wet extreme climate indices are in line with research that indicated crop failure is favoured by decline in rainfall (Abubakar et al., 2020; Sultan et al., 2019a) while rain resumption is potentially favourable to crop yields. Findings on hot extreme indices corroborated that of Vogel et al. (2019) who revealed negative impacts from increased warm day frequencies on crop yields (maize, wheat, rice, soybeans), worldwide. This can be explained by the fact that hot temperatures at the time of flowering can reduce the potential number of seeds or grains formed or developed (Wheeler et al., 2000). Crop yields in the zone have been affected by cold extremes (TNn and TXn). This aligned with Vogel et al. (2019), who indicated that higher frequencies of unusually cold daily minimum temperatures have negative effects on yields of all crop types, except spring wheat. Similarly, Panda et al. (2014) attested that the extreme state of day and night temperatures in India has caused adverse impacts on rice and cereal crops through changes in phenological development and physiological processes.

Although variation in daily temperature in the Sudan-Sahel zone was below the threshold of 30-34°C (Table 4.2), crop yields were adversely affected by average daily temperature and related climate extremes. Furthermore, rainfall in the zone comparatively less affected crop yields, indicating that yields variations over the last decades were more temperature dependent than rain dependent in the Sudan-Sahel zone.

The indices explained a variation of 29.8 – 44.8% in the Sudan-Sahel zone. Thus, in line with Atiah et al. (2021), yield variation is also dependent on nonclimatic conditions or practices (55.2 – 70.2%).

**(iii) Sahel zone**

The results of three fitted multiple linear regression models used to assess the relationship between extreme climate indices and crop yield in the Sahel climatic zone are presented in Table 4.2. Crop yields were found to significantly relate with hot days (TX90p), annual precipitation (PRCPTOT), coldest day (TNn), cold nights (TN10p) and number of heavy rain days (R10mm). Sorghum yield recorded a significant relationship with TX90p and PRCPTOT while cowpea was significantly influenced by TNn and TN10p. Millet yield was found to significantly relate with TN10p and R10mm. The unfavourable climate extreme indices to cowpea yield were TN10p and TNn. A degree increase in the TNn and one percent increase in TN10p frequency could cause a reduction of 28.6 kg/ha and 56.2 kg/ha respectively in cowpea yield. Moreover, one percent increase in TN10p frequency causes a decline in millet yield by about 23.8 kg/ha. The findings of TN10p and TNn impacting cowpea yield negatively was consistent with Panda et al. (2014) in the Sahel zone of Burkina Faso. On the other hand, increased trend of hot extremes, such as a one percent increase in TX90p induced an increase (18.3 kg/ha ) of sorghum yield. This result did not support the claim that hot temperatures at a time of flowering can reduce the potential number of seeds or grains and subsequently, stem crop yield (Wheeler et al., 2000). Finally, wet climate extremes could have been favourable to crop production in the Sahel. A millimetre increase in the total precipitation could induce sorghum yield increase by 1.2 kg/ha while a day increase in the heavy rain days could increase millet yield by 26.7 kg/ha.

In Sahel zone, despite the persistence in some years of average daily temperature beyond the crop requirements (Table 4.2), no significant interrelation was observed with the studied crops. This could mean that related climate extremes (hot days, coldest night, frequency of cold nights) are more responsible for observed variation in crops yields. Crop yield variation (28.6 – 50.2%) in the Sahel zone implies the important role play by non-climatic factors in yield determination (49.8 – 71.4%). More effort at policy and research level must be done to understand the impact of non-climatic factors on yields, including soil fertility, seed and farmers practice, etc.

Overall, the observed variation in crop yields attributable to extreme climate indices is lower than the value reported at a global scale by Vogel et al. (2019). According to these authors, climate extremes indices account for more than half of the explained variances of yield anomalies (maize, rice, soybeans) and nearly half of spring wheat at the global scale. The difference in findings may be attributed to differences in crop types and climate conditions.

The negative impact of climate extremes from this study may not vary much across Sub-Saharan Africa, due to the continuous rise in temperature on the continent and could alter future food security in Africa (Girvetz et al., 2019; Mangani et al., 2019; Paliwal et al., 2020) and even at a global scale (Chadalavada et al., 2021; Ullah et al., 2019).

Table 4.2: Effects of climate indices on crop yields across the three climatic zones of Burkina Faso. α, SE and Adj. $R^2$ represent estimates of regression coefficients, standard error of means and percent adjusted $R^2$, respectively.

| Sudan climatic zone | | | | | | | |
|---|---|---|---|---|---|---|---|
| Models | Coefficient | α | SE | t value | Pr (>t) | Adj.$R^2$ (%) | p-value |
| Cowpea yield (kg/ha) | | | | | | | |
| TX10p+R10mm | Intercept | 255.9 | 195.0 | 1.3 | 0.199 | 47.4 | **0.000** |
| | TX10p (%) | -58.4 | 11.4 | -5.1 | **0.000** | | |
| | R10mm (days) | 22.1 | 5.5 | 4.0 | **0.000** | | |
| Sorghum yield (kg/ha) | | | | | | | |
| TN90p+TMm | Intercept | 11242.4 | 4967.7 | 2.3 | **0.031** | 34.1 | **0.000** |
| | TN90p (%) | 24.6 | 5.8 | 4.3 | **0.000** | | |
| | TMm (°C) | -391.2 | 181.7 | -2.2 | **0.039** | | |
| Millet yield (kg/ha) | | | | | | | |
| TNn+CDD | Intercept | 1465.7 | 219.1 | 6.7 | **0.000** | 23.0 | **0.005** |
| | TNn (°C) | -45.6 | 15.0 | -3.0 | **0.000** | | |
| | CDD (days) | -1.6 | 0.8 | -2.0 | **0.000** | | |
| Millet yield (kg/ha) | | | | | | | |
| TXn+R10mm | Intercept | -2144.7 | 645.1 | -3.3 | **0.002** | 34.8 | **0.000** |
| | TXn (°C) | 97.7 | 23.7 | 4.1 | **0.000** | | |
| | R10mm (days) | 11.8 | 3.2 | 3.2 | **0.003** | | |
| **Sudan-Sahel climatic zone** | | | | | | | |
| Models | Coefficient | α | SE | t value | Pr (>t) | Adj.$R^2$ (%) | p-value |
| Maize yield (kg/ha) | | | | | | | |
| TNn+CSDI | Intercept | 1733.4 | 426.9 | 4.1 | **0.000** | 29.8 | **0.002** |
| | TNn (°C) | -83.8 | 32.8 | -2.6 | **0.016** | | |
| | CSDI (days) | 50.7 | 18.2 | 2.8 | **0.009** | | |
| Groundnut yield (kg/ha) | | | | | | | |
| TXn+CDD | Intercept | 2589.9 | 433.9 | 6.0 | **0.000** | 44.8 | **0.000** |
| | TXn (°C) | -57.7 | 15.9 | -3.6 | **0.001** | | |
| | CDD (days) | -3.4 | 0.9 | -3.9 | **0.001** | | |
| Millet yield (kg/ha) | | | | | | | |
| TNn+R10mm | Intercept | 1099.3 | 336.4 | 3.3 | **0.002** | 39.8 | **0.000** |
| | TNn(°C) | -77.6 | 21.8 | -3.6 | **0.001** | | |
| | R10mm (days) | 17.8 | 6.1 | 2.9 | **0.007** | | |
| **Sahel climatic zone** | | | | | | | |
| Models | Coefficient | α | SE | t value | Pr (>t) | Adj.$R^2$ q(%) | p-value |
| Sorghum yield (kg/ha) | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| TX90p+PRCPTOT | Intercept | -1185.3 | 137.4 | -1.4 | 0.187 | 50.2 | **0.000** |
| | TX90p (%) | 18.3 | 4.3 | 4.2 | **0.000** | | |
| | PRCPTOT (mm) | 1.2 | 0.2 | 5.9 | **0.000** | | |
| Cowpea yield (kg/ha) | | | | | | | |
| TNn+TN10p | Intercept | 884.5 | 462.8 | 1.9 | **0.067** | 28.6 | **0.005** |
| | TNn (°C) | -28.6 | 39.4 | -0.7 | 0.474 | | |
| | TN10p (%) | -56.2 | 16.7 | 16.7 | **0.002** | | |
| Millet yield (kg/ha) | | | | | | | |
| TN10p+R10mm | Intercept | 239.2 | 129.4 | 1.8 | 0.074 | 33.8 | **0.001** |
| | TN10p (%) | -23.8 | 11.6 | -2.1 | **0.048** | | |
| | R10mm (days) | 26.7 | 7.2 | 3.7 | **0.001** | | |

Legend: $P < 0.001$: highly significant; $P < 0.01$ : very significant; $P < 0.05$ : significant; $P > 0.05$ ns: not significant. Source: Author's Own computation, 2023.

### 4.3.2 Susceptibility of livestock diseases to climate change

#### 4.3.2.1 Predictors variables

Principal Component Analysis (PCA) allowed for the reduction of 15 climate indices to components that explained the essence of the original data. The PCA was used to explain 70, 71 and 72 % of the original climate indices in Sudan (Dano), Sudan-Sahel (Niou) and Sahel (Dori) zones, respectively (Appendix 3, 4, 5). These components renamed as new variables, were used as predictors in Poisson Regression Analysis. In the Sudan zone, the climate indices consisted of rainfall, extreme hot days, cold nights and dry spell. In the Sudan-Sahel zone, the variables consisted of extreme hot days, rain intensity, wet spell and dry and cold night events. Finally in the Sahel zone the variables included extreme hot nights, rain intensity, cold and dry days, and cold and wet days (Appendix 3, 4, 5).

#### 4.3.2.2 Susceptibility of livestock diseases to climate extremes across climatic zones

Occurrence of livestock diseases have either been reduced or increased due to climatic factors. The following sections will highlight the relationship between occurrence of livestock diseases and climatic factors for each climatic zone (Table 4.3; Figure 4.5, 4.6, 4.7).

Foot-and-mouth disease occurrence in Sudan zone was significantly increased by extreme hot days (1.7 units) and cold nights (1.5 units) (Figure 4.5a). In the Sudan-Sahel zone, disease occurrence was favoured by wet spell (2.6 units) (Figure 4.6a). The disease occurrence increased by 1.3 and 1.1 units in the Sahel, as the extreme hot night and rainfall intensity increased respectively (Figure 4.7a).

The susceptibility to climate conditions was different along the climate gradient. Hot nights and rainfall intensity were favorable to the disease occurrence in the Sahel. This agreed with previous findings indicating that, the warming trend (Luan et al., 2023; Zhao et al., 2017) and fluctuations in rainfall patterns affected livestock disease outbreaks (Baumgard et al., 2012; Tirado et al., 2010); namely the prevalence, profiles, and sustenance of diseases causal agents including pathogenic bacteria, viruses, parasites, and fungi (Tirado et al., 2010). Overall, wet/dry and hot/cold conditions seem not to have induced the resurgence of Foot-and-mouth diseases across all climatic zones. In the Sudan zone, the occurrence of Pasteurellosis of small ruminants (PSR) is favoured by extreme hot days (increased occurrence by 1.0 unit due to a unit increase in extreme hot days) (Figure 4.5b). This disease occurrence in Sudan-Sahel, increased by 1.1, 1.3 and 1.4 units, due to increase in extreme hot days, rain intensity and wet spells respectively ($P<0.001$) (Figure 4.6b).

In the Sahel zone, a unit increase in the extreme hot night ($P<0.001$) and rain intensity ($P<0.05$) induced an increase by 1.2 and 1.0 units, respectively (Figure 4.7b). Warm and humid weather was therefore favourable to the resurgence of the PSR. FAO (2008) similarly indicated wet and hot conditions to have an impact on microbial ecology and growth, animal physiology, and host susceptibility which may result in the emergence, redistribution, and changes in the incidence and intensity of pest infestations and animal diseases. Inversely, cold nights, rainfall and dry spell in the Sudan zone; dry and cold nights in the Sudan-Sahel; cold and dry days and cold and wet days in the Sahel zone did not induce the occurrence of PSR. For emphasis, associated warm and wet conditions were favourable to the PSR. The Contagious bovine pleuropneumonia (CBPP) resurgence was only induced by dry spell (1.3 increase due to a day increase in dry spell) in the Sudan zone (Figure 4.5c). Unlike, the FMD and PSR, the CBPP is more driven by dry conditions than wet and warm conditions. Indeed, cold nights, rainfall and extreme hot days did not cause the increase in the occurrence of this disease. Moreover, this disease seems to be less susceptible to climate conditions within the Sudan-Sahel and Sahel zones.

In the Sudan-Sahel zone, LSD disease occurrence increases (by 1.0), but non significantly ($P<0.69$) with a unit increase in Wet spell (days) (Figure 4.6c). In the Sahel zone, the Lumpy skin disease (LSD) occurrence increases by 9.4, 1.1 and 2.8 in response to a unit increase in the extreme hot nights, cold and dry days and cold and wet days respectively ($P<0.001$) (Figure 4.7c). It seemed that day warming and dry spell reduced the occurrence of LSD. Indeed, extreme hot days, rainfall intensity and the dry and cold nights in the Sudan-Sahel zone; the rain intensity in the Sahel zone did not cause the increase in the occurrence of the Lumpy skin disease (Figure 4.6c; Figure 4.7c).

The occurrence of Newcastle disease within the Sudan-Sahel zone increased by 1.3 and 3.2 units with a unit increase in the extreme hot days and wet spell respectively ($P<0.001$) (Figure 4.6d).

This disease occurrence increased in the Sahel zone by 1.1 units due to a unit increase in extreme hot nights and cold and dry days ($P<0.001$) (Figure 4.7d). It seemed that night and day cooling affected differently the disease occurrence between the Sudan-Sahel and Sahel zone. Rainfall intensity and dry and cold nights event in the Sudan-Sahel zone, rain intensity and cold and wet days in the Sahel zone did not induce an increase in the occurrence of Newcastle disease. With regards to the role of rainfall, Sese et al. (2022), working in a humid equatorial highlands with 1500 mm average annual rainfall, reported an increase in the spread of Newcastle disease. The difference may be due to the differences between climatic conditions of the study areas.

The Sudan-Sahel and Sahel zones showed differences in livestock vulnerability to LSD and Newcastle disease. This might be due to differences in climate conditions between the two zones. The Sahel zone was characterized by day and night cooling while Sudan-Sahel was characterized by day and night warming (see 3.3.6.2 Table 3.5).

Overall, across zones, several climate extremes revealed a significant association with the resurgence of the studied livestock diseases. This corroborated previous literature (Baumgard et al., 2012; Reperant 2010 ; Chomel et al. 2007; Woolhouse and Gaunt 2007; Jones et al. 2008; Wolfe et al. 2005).

Climate change influenced several factors that cause livestock disease outbreaks, mainly associated with temperature rise, host pathogen interaction, farming practices, number of vectors/host/reservoirs, environmental factors and microhabitats (Baumgard et al., 2012). The changing climate pattern could favour the migration of some agents responsible for diseases outbreak and thus converting some disease outbreaks from endemic to epidemic (Baumgard et al., 2012; Trape et al., 1996). The most affected were the Newcastle disease, the Foot-and-mouth disease, the Pasteurellosis of small ruminants and Lumpy skin disease. Furthermore, even though they may be favorable to the proliferation and survival of exogenous bacteria and parasites, extremely hot conditions sometimes stem the resurgence of livestock diseases (FAO, 2008; Bradley et al., 2005; Randolph et al., 2008; Šumilo et al., 2009). Vectors such as insects may also benefit from climate change where warming conditions will result in higher parasite abundance and increased disease incidence (Baumgard et al., 2012; Wall and Ellse, 2011).

Besides climatic conditions, non-climatic factors may have also significantly influenced occurrence of livestock diseases across the study zones. Non- climatic factors can involve the stress associated with handling, transport or housing (Colville, 2007).

Table 4.3: Effects of climate indices on livestock diseases occurrence across climatic zones of Burkina Faso. The estimate values gives the logarithm of the response variable.

| Sudan zone | | | | | Sudan-Sahel zone | | | | | Sahel zone | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Foot-and-mouth disease | | | | | Foot-and-mouth disease | | | | | Foot-and-mouth disease | | | | |
| Variables | Estimate | Std. Error | z value | Pr(>\|z\|) | Variables | Estimate | Std. Error | z value | Pr(>\|z\|) | Variables | Estimate | Std. Error | z value | Pr(>\|z\|) |
| (Intercept) | 6.48 | 0.01 | 562.49 | **0.000** | (Intercept) | 6.68 | 0.01 | 630.21 | **0.000** | (Intercept) | 6.09 | 0.01 | 494.27 | **0.000** |
| Rainfall (mm) | -0.64 | 0.01 | -57.96 | **0.000** | Extreme hot days (%) | -0.79 | 0.01 | -97.96 | **0.000** | Extreme hot night (%) | 0.27 | 0.01 | 24.77 | **0.000** |
| Extreme hot days (%) | 0.50 | 0.01 | 55.28 | **0.000** | Rain intensity (mm/d) | -0.78 | 0.01 | -94.60 | **0.000** | Rain intensity (mm/d) | 0.10 | 0.01 | 7.27 | **0.000** |
| Cold nights (%) | 0.40 | 0.01 | 38.54 | **0.000** | Wet spell (days) | 0.96 | 0.01 | 117.61 | **0.000** | Cold and dry days | -0.57 | 0.01 | -55.58 | **0.000** |
| Dry spell (days) | -1.25 | 0.02 | -72.83 | **0.000** | Dry and cold nights event (days) | -0.35 | 0.01 | -51.56 | **0.000** | Cold and wet days | -0.21 | 0.01 | -17.92 | **0.000** |
| Pasteurellosis of small ruminants | | | | | Pasteurellosis of small ruminants | | | | | Pasteurellosis of small ruminants | | | | |
| Variables | Estimate | Std. Error | z value | Pr(>\|z\|) | Variables | Estimate | Std. Error | z value | Pr(>\|z\|) | Variables | Estimate | Std. Error | z value | Pr(>\|z\|) |
| (Intercept) | 4.34 | 0.03 | 155.19 | **0.000** | (Intercept) | 3.98 | 0.04 | 112.85 | **0.000** | (Intercept) | 5.20 | 0.02 | 271.94 | **0.000** |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall (mm) | -0.14 | 0.04 | -3.78 | **0.000** | Extreme hot days (%) | 0.06 | 0.03 | 1.83 | 0.068 | Extreme hot night (%) | 0.17 | 0.02 | 10.19 | **0.000** |
| Extreme hot days (%) | 0.03 | 0.03 | 0.84 | 0.400 | Rain intensity (mm/d) | 0.23 | 0.04 | 6.45 | **0.000** | Rain intensity (mm/d) | 0.04 | 0.02 | 1.94 | **0.052** |
| Cold nights (%) | -0.17 | 0.03 | -5.11 | **0.000** | Wet spell (days) | 0.32 | 0.03 | 11.02 | **0.000** | Cold and dry days | -0.14 | 0.02 | -8.50 | **0.000** |
| Dry spell (days) | -0.12 | 0.04 | -3.16 | **0.002** | Dry and cold nights event (days) | -0.36 | 0.04 | -9.21 | **0.000** | Cold and wet days | -0.47 | 0.02 | -25.40 | **0.000** |
| Contagious bovine pleuropneumonia | | | | | Lumpy skin disease | | | | | Lumpy skin disease | | | | |
| Variables | Estimate | Std. Error | z value | Pr(>\|z\|) | Variables | Estimate | Std. Error | z value | Pr(>\|z\|) | Variables | Estimate | Std. Error | z value | Pr(>\|z\|) |
| (Intercept) | 3.66 | 0.04 | 88.83 | **0.000** | (Intercept) | 5E+00 | 2E-02 | 2E+02 | **0E+00** | (Intercept) | 1.98 | 0.12 | 16.41 | **0.000** |
| Rainfall (mm) | -0.22 | 0.05 | -4.30 | **0.000** | Extreme hot days (%) | -4E-01 | 2E-02 | -2E+01 | **3E-77** | Extreme hot night (%) | 2.24 | 0.07 | 31.97 | **0.000** |
| Extreme hot days (%) | -0.28 | 0.04 | -6.42 | **0.000** | Rain intensity (mm/d) | -8E-02 | 2E-02 | -3E+00 | **7E-04** | Rain intensity (mm/d) | -0.40 | 0.10 | -4.08 | **0.000** |
| Cold nights (%) | -0.29 | 0.04 | -6.57 | **0.000** | Wet spell (days) | 9E-03 | 2E-02 | 4E-01 | **7E-01** | Cold and dry days | 0.09 | 0.02 | 3.64 | **0.000** |
| Dry spell (days) | 0.24 | 0.04 | 5.59 | **0.000** | Dry and cold nights event (days) | -2E-01 | 2E-02 | -1E+01 | **2E-23** | Cold and wet days | 1.02 | 0.11 | 8.95 | **0.000** |

| | Newcastle | | | | Newcastle | | | |
|---|---|---|---|---|---|---|---|---|
| Variables | Estimate | Std. Error | z value | Pr(>\|z\|) | Variables | Estimate | Std. Error | z value | Pr(>\|z\|) |
| (Intercept) | 4.45 | 0.03 | 140.88 | **0.000** | (Intercept) | 5.54 | 0.02 | 340.15 | **0.000** |
| Extreme hot days (%) | 0.27 | 0.03 | 10.64 | **0.000** | Extreme hot night (%) | 0.14 | 0.01 | 10.34 | **0.000** |
| Rain intensity (mm/d) | -0.25 | 0.02 | -10.37 | **0.000** | Rain intensity (mm/d) | -0.42 | 0.01 | -30.17 | **0.000** |
| Wet spell (days) | 1.17 | 0.02 | 48.38 | **0.000** | Cold and dry days | 0.13 | 0.01 | 8.64 | **0.000** |
| Dry and cold nights event (days) | -0.24 | 0.03 | -9.26 | **0.000** | Cold and wet days | -0.40 | 0.01 | -26.98 | **0.000** |

Legend: P < 0.001: highly significant; P < 0.01 : very significant; P < 0.05 : significant; P > 0.05 ns: not significant. Source: Author’s Own computation, 2023.

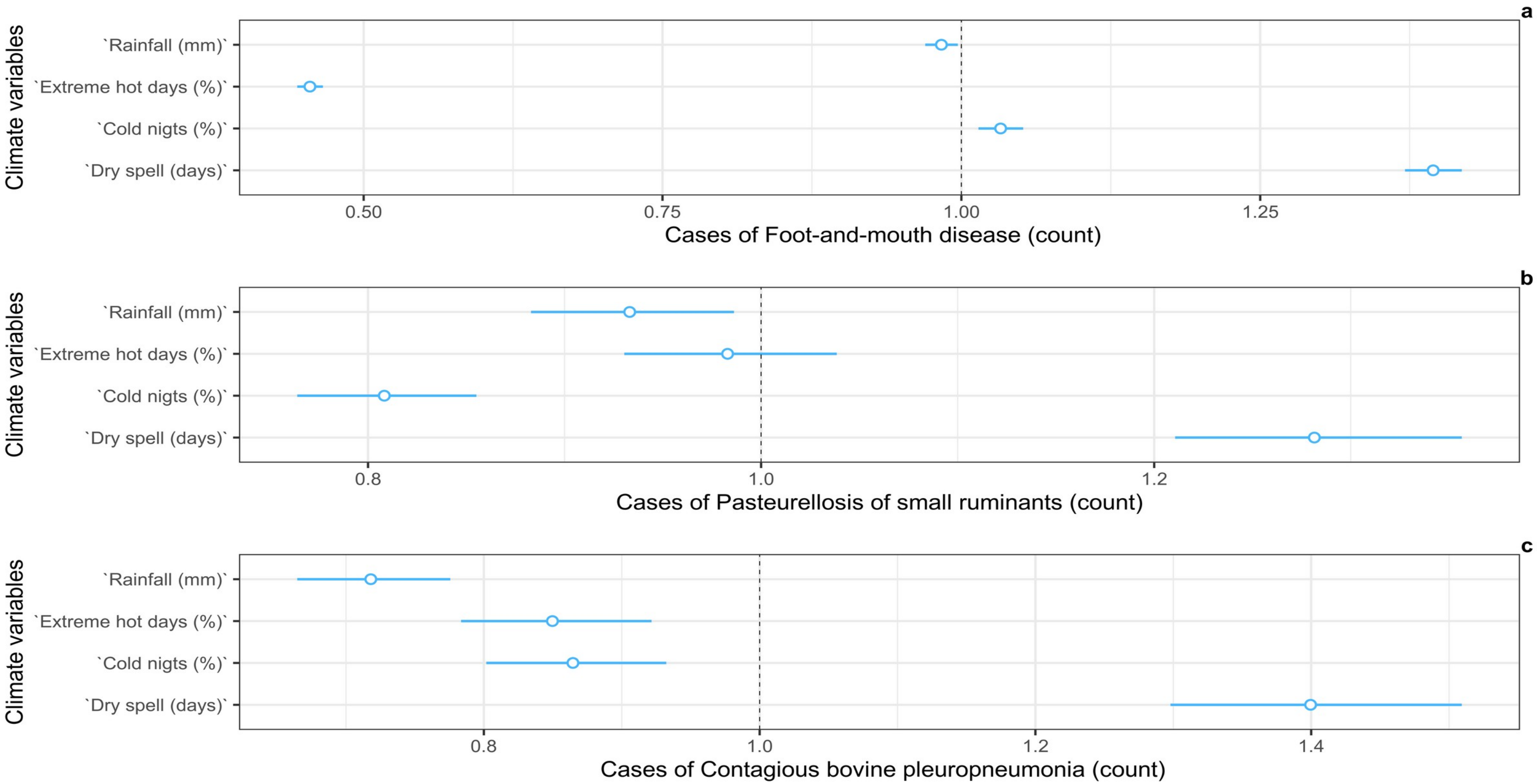


Figure 4.5: Influence of climate conditions on the occurrence of Foot-and mouth disease (a), Pasteurellosis of Small Ruminants (b) and Contagious bovine pleuropneumonia (c) in Sudan climatic zone of Burkina Faso. Cases correspond to the exponentiated values of the estimates obtained from the Poisson regression analysis. Value lower than 1 indicates a negative association between climate indices and diseases occurrence while value greater than 1 indicate positive association. The horizontal lines around dots indicate the confidence interval of each predicted case. Source: Author’s Own computation, 2023.

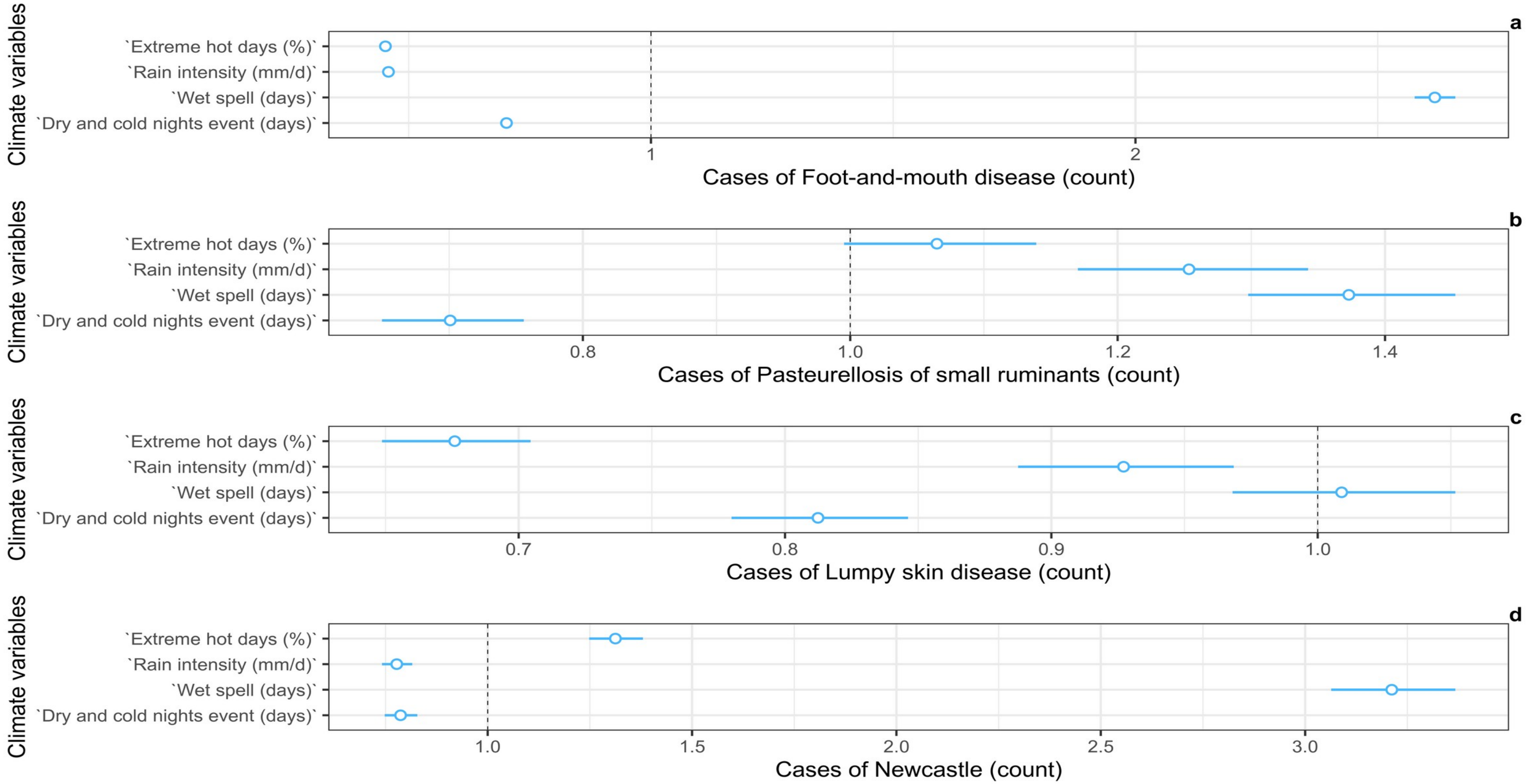


Figure 4.6: Influence of climate conditions on the occurrence of Foot-and-mouth disease (a), Pasteurellosis of small ruminants (b), Lyumpy skin disease (c) and Newcastle (d) in Sudan-Sahel climatic zone of Burkina Faso. Cases correspond to the exponentiated values of the estimates obtained from the Poisson regression analysis. Value lower than 1 indicates a negative association between climate indices and diseases occurrence while value greater than 1 indicate positive association. The horizontal lines around dots indicate the confidence interval of each predicted case. Source: Author's Own computation, 2023.

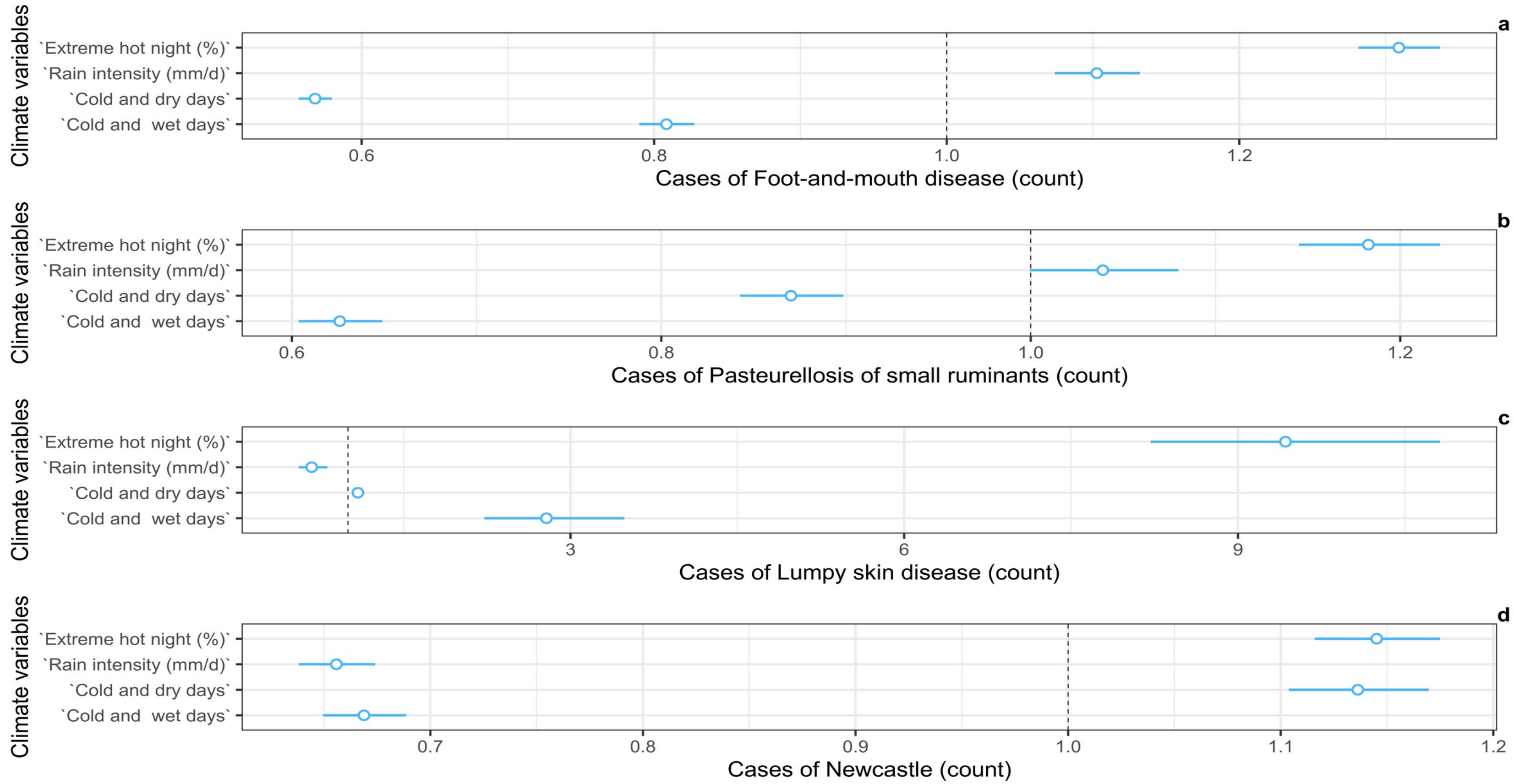


Figure 4.7: Influence of climate conditions on the occurrence of Foot-and-mouth disease (a), Pasteurellosis of small ruminants (b) Lyumpy skin disease (c) and Newcastle (d) in the Sahel climatic zone of Burkina Faso. Cases correspond to the exponentiated values of the estimates obtained from the Poisson regression analysis. Value lower than 1 indicates a negative association between climate indices and diseases occurrence while value greater than 1 indicate positive association. The horizontal lines around dots indicate the confidence interval of each predicted case. Source: Author's Own computation, 2023.

## 4.4 Conclusion

Across all the climatic zones, major crops and livestock species are exposed to the impacts of climate change and variability. Crop yields, and the occurrence of livestock disease, responded differently to climate extremes in the previous decades. Some of them demonstrated positive impacts through yield increase and reduction of the studied livestock diseases. Conversely, the majority of the climate extremes adversely affected both yield through crop failure and some contributed strongly to the resurgence of livestock diseases. The influence of climate extremes on the occurrence of animal diseases has been more pronounced than for crop production. However, some variation in crop yields and the occurrence of livestock diseases could not be explained by the climate extremes studied. Other parameters possibly responsible for this variation could be non-climatic, such as crop farming and livestock breeding practices, use of improved seeds and breeds, soil fertility, feed quality and availability etc. Therefore, further investigation is needed on the implications of these non-climatic factors on crop production and animal health in Burkina Faso. The adverse effects of climate extremes can be mitigated by more resilient crop and livestock breeds. Furthermore, appropriate farming and breeding conditions should be adopted to minimize the influence of non-climatic factors on crop failure and livestock disease resurgence. Also, crop-livestock integration could be an option to mitigate both the risks associated with climatic and non-climatic factors to enhance livelihoods and build resilience in Burkina Faso.

# CHAPTER 5: CROP-LIVESTOCK INTEGRATION IN BURKINA FASO: INTEGRATION INDICATORS FOR A HOLISTIC CHARACTERISATION


## ABSTRACT

Global climate change is affecting people's livelihoods, especially smallholder farmers across West Africa. Crop-livestock integration (CLI) offers opportunity to farmers to build climate resilience to the changing climate. Nevertheless, the characteristics of such mixed-farming system is poorly documented in Burkina Faso. Thus, the current research aims to develop or update measurement tools known as CLI indicators for a holistic characterisation of the mixed farming. These indicators were based on farmers' households survey and secondary data. Results indicate that majority of the farmers (91.6%) in the Sudan-Sahel zone are practising full crop-livestock integration, unlike the Sahel (62.3%) and Sudan (48.2%) zones. The average level of integration was higher in Sudan-Sahel (97.7 ± 8.1%) than Sahel (88.1 ± 17.0%) and Sudan (79.9 ± 22.9%) zones. Effective integration was realised by only 5.1%, 10.5% and 14.8% of households in Sudan, Sahel, and Sudan-Sahel zones respectively. CLI was comparatively more effective in the Sudan-Sahel (65.9±32.0%) than Sahel (44.9±29.5%) and Sudan (35.6±35.0%) zones. Inversely the integration was more efficient in the Sahel (33.2±25.5 kg DM/man.day) than Sudan (18.4±17 kg DM/man.day) and Sudan-Sahel (13.7±12.0 kg DM/man.day) zones. The integration effectiveness was positively predicted by the level of integration only in the Sudan zone ($R^2$adj =0.26, pvalue =2.72e$^{-14}$). Moreover, the efficiency was positively correlated with the effectiveness in the Sudan-Sahel ($R^2$adj =0.12, pvalue =4.66e$^{-07}$) and Sahel ($R^2$adj =0.065, pvalue =4.69e$^{-04}$) zones. The financial integration was very weak and not significantly different between climatic zones. CLI is underperforming in Burkina Faso and can potentially be improved through more effort toward crop residues and manure mobilisation and increased draft power utilisation. The indicators described herein attempted a holistic description of CLI across West Africa.

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Key words: crop-livestock integration, indicators, West Africa

## 5.1 Introduction

Global change remains and will remain a challenging issue in the next decades for both mankind and its living environment. This global change encompassing climate change, growing population (United Nations, 2019) and environmental degradation (Lemaire et al., 2019, 2013a) affects livelihoods and resilience capacity of low income people (Lemaire et al., 2019; Paillard et al., 2014) worldwide and particularly across West Africa. Growing challenges are likely to be severely experienced across West Africa by poor and smallholder farmers. There is an urgent need for such farmers to adopt suitable adaptation and mitigation actions/strategies in order to cope with the impacts of the observed challenges.

Among coping strategies, crop-livestock integration constitutes an accessible practice to small farmers who aim at diversifying their production and reduce shocks and challenge. This has, for long time, been a traditional and common practice across SSA and the West African agro-ecological systems, with several advantages in sustaining farmers' livelihoods. Indeed, this practice limits external inputs (especially chemicals) and ensures some economic and environmental benefits (Alary et al., 2017; Lemaire et al., 2013a; Ryschawy et al., 2012; Vall et al., 2017), thus constituting a real opportunity for low-income farmers in a context of global challenges. Mixed farming systems, including the integrated crop-livestock system, are the present and the foreseeable future of West African livestock systems (Williams et al., 2004) for farmers' resilience building in general (Alary et al., 2017). Several studies worldwide and in West Africa including Burkina Faso, have been conducted on crop-livestock integration. The majority dealt with the implication of mixed farming practice on the ecological and socio-economic aspects of its adoption (Bansal et al., 2022; Lemaire et al., 2013a; Rai et al., 2021; Sulc and Franzluebbers, 2014; Sulc and Tracy, 2007). Studies in Burkina Faso highlighted CLI role in production diversification and sustainability (Ayenan, 2017; Bénagabou et al., 2017; Vall et al., 2019, 2006; Zoundi et al., 2006) and energy use efficiency (Bénagabou et al., 2017). Some studies dwelt on CLI indicators for the characterisation of the system (Bénagabou et al., 2017, 2013; Rasambatra et al., 2020; Vall et al., 2017). Integrated crop-livestock system (ICLS) is a farming strategy that involves numerous practices which implementation allows bio-physical (Lemaire et al., 2019) and financial (Sumberg, 2003) resource exchanges among the livestock and crop modules. The financial flux is an opportunity to sustain the bio-physical exchanges (manure, crop-residues, draft-power). This conception aligns with the detailed description of ICLS along four dimensions (space, time, ownership, and management) in the context of exchanges between the system components of biomass, manure, animal power and/or financial resources (Sumberg, 2003). According to this author, crop-livestock interactions are thus the manifestation of these exchanges in a process combining agro-ecological and economic contexts with farmers' personal and socio-economic circumstances that determine the motivation for, form and extent of such exchanges. Lemaire et al. (2019) further characterised crop-livestock integration across West Africa as the exchange of field manuring against livestock feeding on post-harvest resources (regrowth, crop residues) and agricultural by-products (brans, cakes) for diet supplementation.

At the current state of the research both at global scale and West Africa in particular, few investigations were done on all the integration dimensions developed by Sumberg (2003) especially the financial resource exchanges (Ewing et al., 2004; Sumberg, 2003) among the integrated system components. The research works generally focused on the space and time dimension of the integration and resource exchanges focusing on bio-physical resources (manure, forage and draft power) (Bénagabou, 2018; Vall et al., 2019, 2017).

Several other studies tended to define indicators to measure the level of integration between crop and livestock modules. Some tend to define the integration base on the rate of organic carbon retention in farm soils on the yearly basis (Vall et al., 2017); others based it on the amount of manure produced by Tropical Livestock Unit (TLU), the coverage of livestock needs in protein and energy (Delma et al., 2016; Rasambatra et al., 2020). Other authors measured the integration based on the coverage of cropland manure needs (Bénagabou, 2018; Bénagabou et al., 2013; Vall et al., 2011) and the level of nitrogen amendment per hectare (kg/ha) (Rasambatra et al., 2020). CLI indicators were defined in Burkina Faso along the space and time dimensions and around manure, biomass, and animal power resources (Bénagabou, 2018; Bénagabou et al., 2013). These were defined in terms of coverage of manure needs (CoMN), of fodder needs (CoFN) and of draft power needs (CoDPN) and described as accounting for the level of crop-livestock integration. This description as the measure of the level of CLI through a global indicator (GI) (Bénagabou et al., 2013), could be better described as a set of measurement indicators of rather the effectiveness of integration of crop and livestock activities. The level of integration relates to the complexity of interrelations between the system components. This complexity spans from weak (one or few integration practices) to strong integration involving more interactions between the system components. This study seeks to make a clear distinction between integration effectiveness (IE) and the level of integration (LI). Moreover, the study seeks to integrate the financial resources (Sumberg, 2003) in the development of crop-livestock indicators. The concepts of active and passive CLI developed by (Bénagabou, 2018; Bénagabou et al., 2017) were also adopted for the study. Bénagabou (2018) defined active integration as “the coverage of fodder needs and the production of organic manure per Tropical Livestock Unit (TLU)” and passive integration as “the production of organic manure per unit surface area”. The current research rather considered the distinction of the two integration categories only in the perceptive of effort made or not made by farmers to fulfil the purposes or the ‘raison d’être’ of the integration. In that perspective, only free grazing of livestock on crop-residues in farm or the fertility transfer through manure deposition (whether per TLU or per unit surface) on farm by mobile livestock will be seen as passive integration in this work. Due to the lack of reliable data on the herd mobility pattern within the study area (numbers and grazing duration on farms) and on the yearly amount of manure passively deposited by mobile herds on farms, the current study did not consider passive integration (though it exists within the study zones) in the computation of integration indicators.

The objectives of this study were to:

1. develop a new set of indicators as assessment tools of crop-livestock integration within smallholder agroecosystems.
2. perform a holistic characterisation of crop-livestock integration across the three climatic zones of Burkina Faso.

We hypothesized that Crop-livestock integration performance varies across the three climatic zones of Burkina Faso, potentially due to the distinct climate conditions of each zone.

## 5.2 Study methods

### 5.2.1 Study area

The characterisation of crop-livestock integration was done across climatic zones within the districts of Dori (13°45'36"N / 14°19'12"N and 0°24'0"W / 0°16'12" E), Niou (12°40'12" / 12°54'36"N and 1°58'48" W / 1°41'24"W) and Dano (10°58'48" / 11°12'36"N and 3°6'36" W / 2°57'0"W (Figure 1) belonging to the Sahel, Sudan-Sahel and Sudan zones respectively. Livestock and crop farming represent the two main socio-economic activities in the study sites. Livestock rearing is more practiced in the Sahel than cropping. Inversely, in the Sudan zone where rainfall is more favourable, farming systems are more crop-oriented. Nevertheless, in a real world there is usually an integration of crop and livestock activities that can be on a continuum of degrees of integration, from 'nil' to 'full'(Sumberg, 2003).

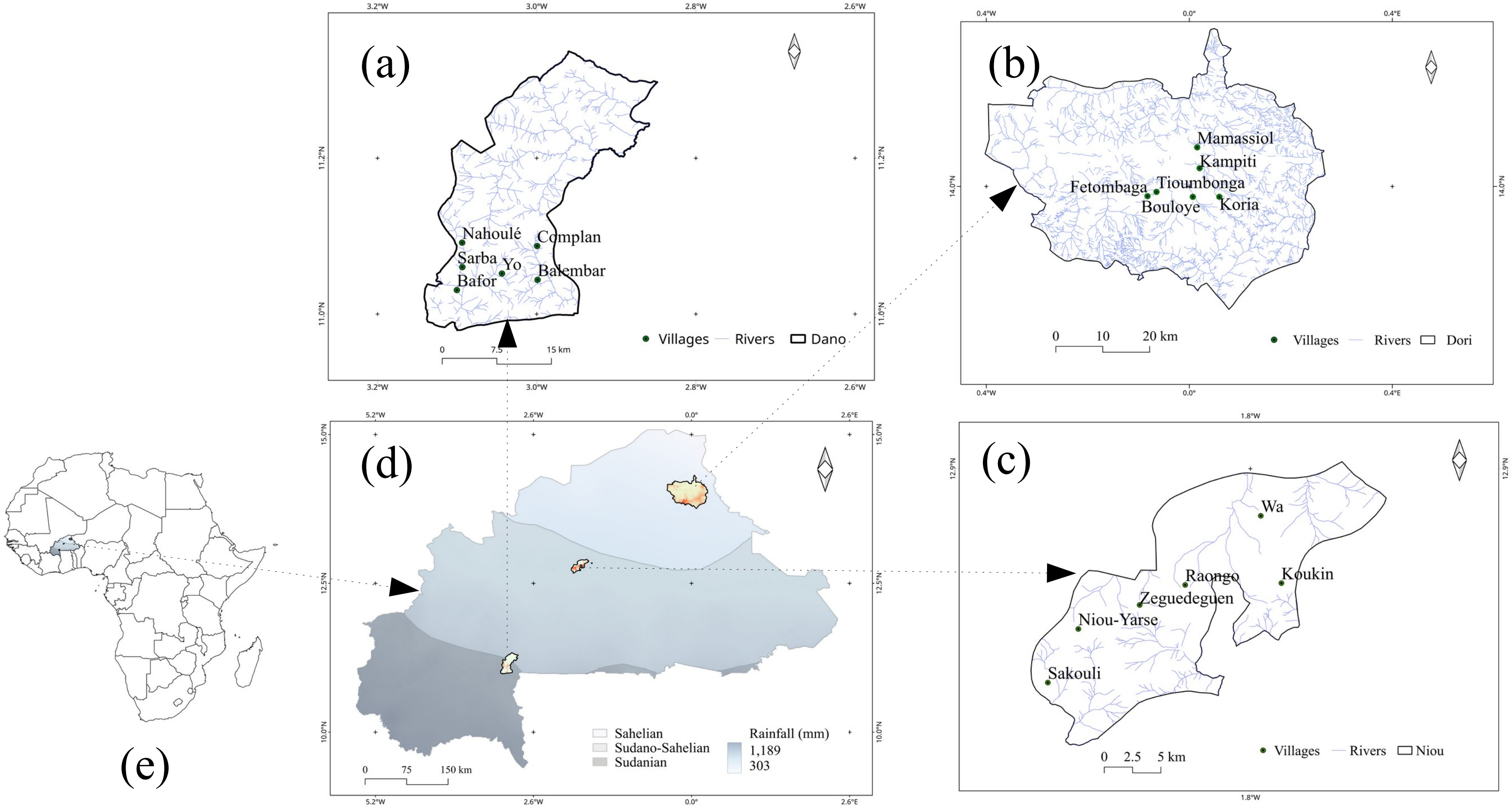


Figure 5.1: Location of the study districts across climatic zones of Burkina Faso. (a) Dano district in the Sudan zone; (b) Dori district in the Sahel zone; (c) Niou district in the Sudan-Sahel zone; (d) and (e) Map of Burkina Faso and Africa respectively. Source: Author's Own computation, 2023.

### 5.2.2 Data collection

Crop-livestock integration description requires a set of data including livestock ownership, land holding, household members efforts in resources (manure and crop-residues collection) mobilization. These data were generated from primary and secondary data and both through interviews and discussion with key informants including livestock and agriculture department extension services.

#### 5.2.2.1 Sampling method

A sampling of surveyed villages was first done with the assistance of state extension services within each municipality. The villages of each municipality were first classified by order of importance (low, medium, high) of integration activities in practice in the village. Also, a purposively random sampling was done to select a set of six (6) villages in each municipality. The number of interviewed farmers was determined following the Dagnelie formula (Equation 5.1) (Babanawo et al., 2022; Dimobe et al., 2018; Lokonon et al., 2021).

$$n = U^2_{1-\alpha/2}[p(1-p)/d^2] \quad \text{Equation 5.1.}$$

where:

*n* is the total number of informants within a locality;

*U* is the value of the normal random variable (1.96 for α =0.05),

*P* is the estimated proportion of the interview respondents (expressed as decimal), assumed to be 0.5 (50%) (Babanawo et al., 2022).

*d* is the predetermined margin of error for the survey (*d* is equal to 4.03%).

The total targetted sample size for this study was therefore estimated at n = 540 farmers (Table 5.1). Nevertheless, the total population actually involved in the study was 589 households made up of 195, 203 and 191 households in Dano (Sudan zone), Niou (Sudan-Sahel zone) and Dori (Sahel zone) municipalities respectively, where at least thirty (30) individual farmers were interviewed about the crop-livestock farming systems (Table 5.1).

The collected information on crop and livestock production covers a period of twelve (12) months given the farmers' inability to give detailed and reliable information beyond a period of one year.

Table 5.1: Sample size of respondents by village and districts

| Districts | Villages | Number of households | | Ethnic group | | | Residence status | | Marital status | | | Sex | | Age |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Targetted | Surveyed | Dagara | Mossi | Fulani | Native | Non-native | Married | Single | Widow | M | F | |
| Dano (Sudan zone) | Bafor | 30 | 32 | 30 | 2 | 0 | 30 | 2 | 32 | 0 | 0 | 32 | 0 | 45.8±12.5 |
| | Bolembar | 30 | 34 | 34 | 0 | 0 | 34 | 0 | 34 | 0 | 0 | 34 | 0 | 46.4±10.5 |
| | Complan | 30 | 32 | 32 | 0 | 0 | 32 | 0 | 32 | 0 | 0 | 32 | 0 | 47.2±9.6 |
| | Nahoulé | 30 | 32 | 29 | 0 | 3 | 27 | 5 | 31 | 0 | 1 | 31 | 1 | 41.2±10.8 |
| | Sarba | 30 | 32 | 32 | 0 | 0 | 31 | 1 | 32 | 0 | 0 | 32 | 0 | 46.4±10.4 |
| | Yo | 30 | 33 | 33 | 0 | 0 | 32 | 1 | 32 | 1 | 0 | 33 | 0 | 41.5±13.4 |
| | **Total Dano** | **180** | **195** | **190** | **2** | **3** | **186** | **9** | **193** | **1** | **1** | **194** | **1** | **44.8±11.4** |
| Niou (Sudan-Sahel) | Koukin | 30 | 33 | 0 | 33 | 0 | 33 | 0 | 32 | 1 | 0 | 33 | 0 | 47.5±10.7 |
| | Niou-Yarcé | 30 | 30 | 0 | 30 | 0 | 30 | 0 | 30 | 0 | 0 | 30 | 0 | 50.7±8.8 |
| | Raongo | 30 | 35 | 0 | 35 | 0 | 35 | 0 | 33 | 0 | 2 | 34 | 1 | 49.1±12.2 |
| | Sakouli | 30 | 35 | 0 | 35 | 0 | 33 | 2 | 35 | 0 | 0 | 35 | 0 | 49.3±12.7 |
| | Wa | 30 | 40 | 0 | 40 | 0 | 40 | 0 | 39 | 0 | 1 | 39 | 1 | 51.9±10.3 |
| | Zeguedghin | 30 | 30 | 1 | 27 | 2 | 30 | 0 | 29 | 0 | 1 | 29 | 1 | 47.5±8.8 |
| | **Total Niou** | **180** | **203** | **1** | **200** | **2** | **201** | **2** | **198** | **1** | **4** | **200** | **3** | **49.4±10.8** |
| Dori (Sahel) | Bouloye | 30 | 30 | 0 | 0 | 30 | 30 | 0 | 30 | 0 | 0 | 30 | 0 | 43.3±10.4 |
| | Fétombaga | 30 | 30 | 0 | 0 | 30 | 30 | 0 | 30 | 0 | 0 | 30 | 0 | 48.0±14.6 |
| | Kampiti | 30 | 41 | 0 | 0 | 41 | 41 | 0 | 37 | 1 | 3 | 37 | 4 | 42.8±13.6 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Koria | 30 | 30 | 0 | 0 | 30 | 30 | 0 | 30 | 0 | 0 | 29 | 1 | 51.1±11.5 |
| Mamassiole | 30 | 30 | 0 | 0 | 30 | 30 | 0 | 30 | 0 | 0 | 30 | 0 | 49.1±11.7 |
| Tchoumbonga | 30 | 30 | 0 | 0 | 30 | 30 | 0 | 27 | 0 | 3 | 24 | 6 | 47.4±14.4 |
| **Total Dori** | **180** | **191** | **0** | **0** | **191** | **191** | **0** | **184** | **1** | **6** | **180** | **11** | **46.7±13.0** |
| **Total zones** | **540** | **589** | **191** | **202** | **196** | **578** | **11** | **575** | **3** | **11** | **574** | **15** | **47±11.9** |

Source: Author's Own computation, 2023.

#### 5.2.2.2 Crop residues and manure quantification

The estimation of the quantity of crop-residues stored by farmers as livestock feed was done by converting the quantity declared during survey and expressed in local measurement units (a pile, a cartload or wheelbarrow full of crop-residues). The conversion was into kilogram using conversion factors derived both from *in situ* measurements and from a fact sheet of the Institute of Environment and Agricultural Research (INERA) of Burkina FASO (Zougmoré et al., 2000) (Table 5.2). Inversely, manure quantification was done by converting into kilogram the quantity declared by farmers during the survey and expressed in local measurement units (a cartload or wheelbarrow full of manure). The conversion factors used were derived from INERA fact sheet (Zougmoré et al., 2000).

Table 5.2: Conversion factors from local measurement units to kilogram

| Designation | Local measurement unit | | Equivalent in kilogram |
|---|---|---|---|
| Crop-residues | Cartload of sorghum straw | | 35 kg |
| | Wheelbarrow full of sorghum straw | | 8.75 kg |
| Manure | Cartload of dung | | 206 kg |
| | Dish filled with compost | Fresh | 30 kg |
| | | Dry | 14.1 kg |
| | Wheelbarrow full of compost | Fresh | 60.5 kg |
| | | Dry | 28.5 kg |
| | Cartload of compost | Fresh | 250 kg |
| | | Dry | 117.5 kg |

Source : INERA Burkina Faso (Zougmoré *et al.,* 2000)

### 5.2.3 Data analysis

#### 5.2.3.1 Conceptual framework of crop-livestock integration

The coupling between crop and livestock production must be analysed at all levels of organisation including: (i) the field, where biogeochemical processes are operating; (ii) the farm, where management decisions are made; (iii) the landscape, where ecosystem processes and interactions between land use components are occurring; (iv) and the region or the continent level, where socio-economic and political constraints are driving forces (Lemaire et al., 2013a) (Figure 5.2).

All the scales of organisations are captured by the conceptual frameworks (Figure 5.2 to 5.4) used for a holistic characterisation of crop-livestock integration within agroforestry systems across arid and semi-arid zones of Burkina Faso. Indeed, all these scales were interrelated with crop-livestock integration dimensions.

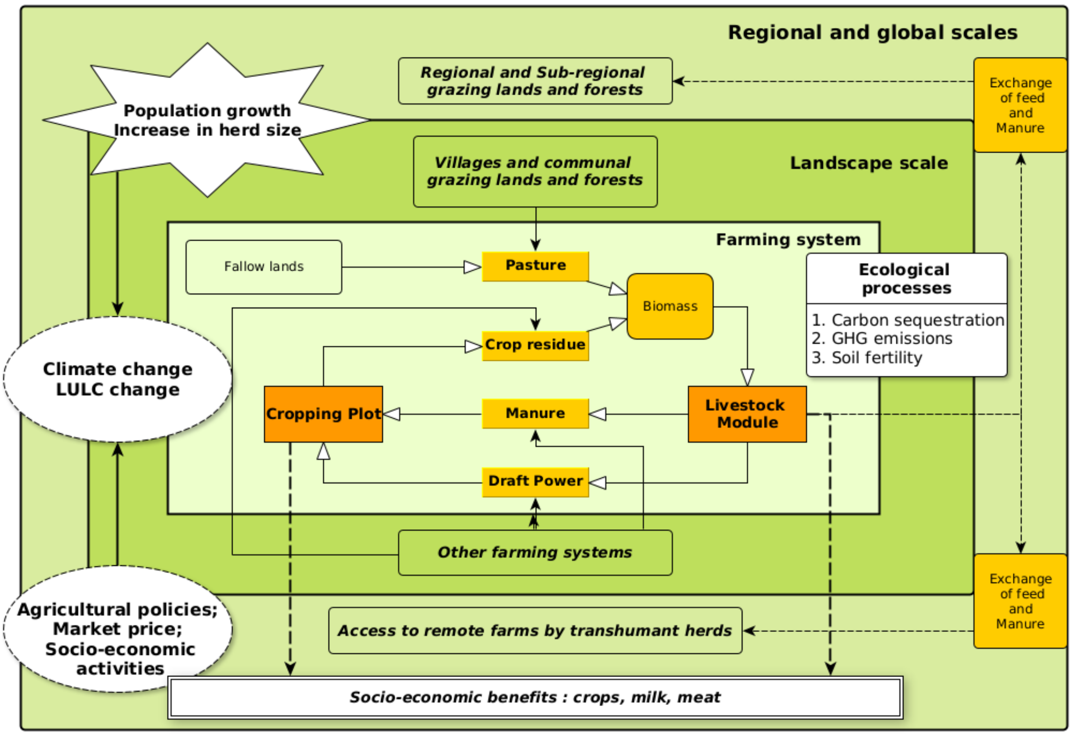


Figure 5.2: Overview on crop-livestock integration, changes drivers, benefits, and ecological processes. Population growth, socio-economic activities, policies, climate and LULC changes influence the integration benefits and ecological performances. The integration is based on resources exchanges between cropping plot and livestock module. A practice to ensure each exchange (manure, fodder, power) refers to an integration practice. Source: Author's Own construction, 2023.

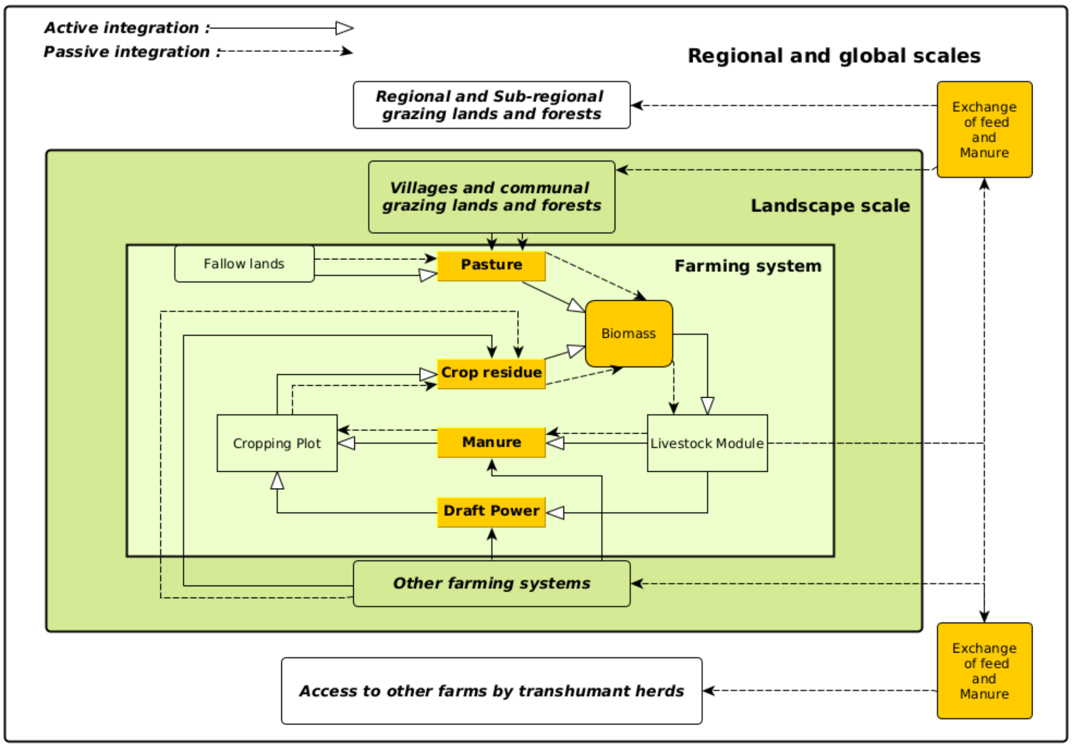


Figure 5.3: Active and passive crop-livestock integration pathways. All transfers of matters between cropping plot and livestock module through production, collection, transportation and storage of such matters refer to active integration. Fertility transfer and access to crop-residues through livestock mobility between villages, between communal and even trans-border farming landscapes refers to passive integration supported by livestock with no or little effort made by livestock keepers. Source: Author's Own construction, 2023.

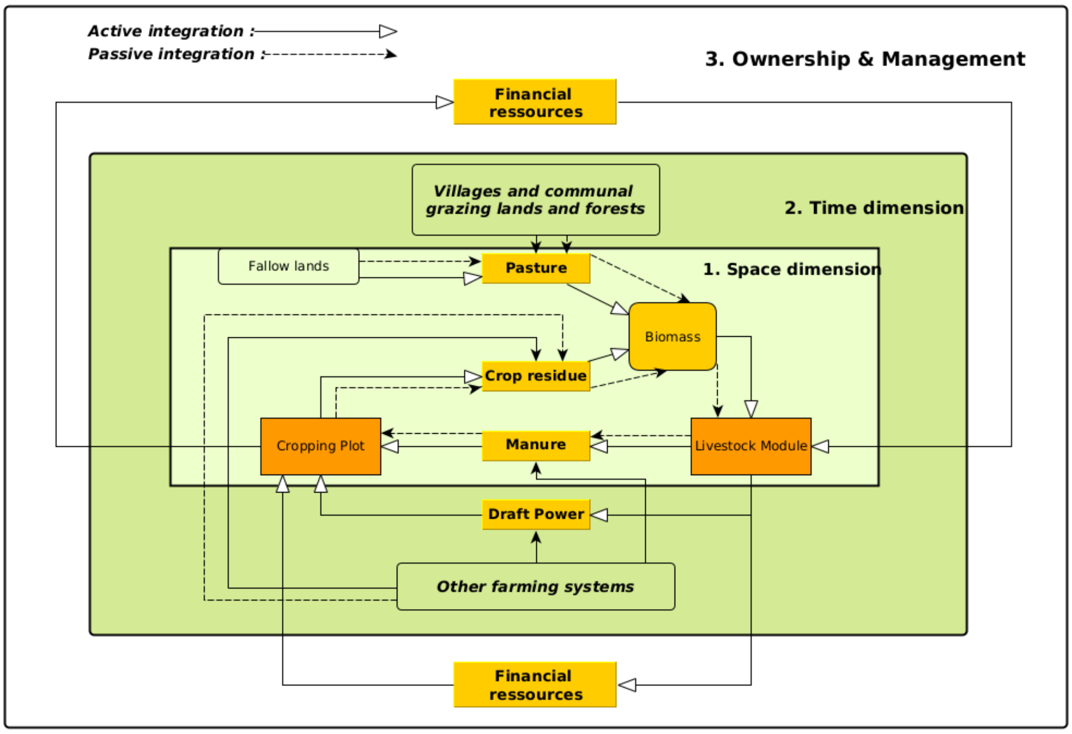


Figure 5.4: Interaction between the type (active or passive) of crop-livestock integration and dimensions of integration. The integration can be observed along space, time, ownership and management dimensions. The passive integration is more of space and time while the active integration is characteristic of space, time, ownership, and management dimensions. Source: Author's Own construction, 2023.

#### 5.2.3.2 Crop-livestock integration indicators

Crop-livestock interactions were characterised through a set of indicators including the following:

***(i) The level of crop-livestock integration*** is investigated based on crop-livestock interactions (i.e exchanges) in terms of crop residues, manure, animal power and financial resources along four obvious and interrelated dimensions (space, time, ownership and management) (Sumberg, 2003). A score of one (1) was considered for any resource exchange. The level of integration is therefore computed as a ratio of the sum of the individual score for each resource flow to the total possible resources flow multiplied per hundred. The level of integration (LI) involves all the resources exchanges (manure, fodder, draft-power, finance) while a level of bio-physical integration ($LI_{bio}$) involved only the exchanges of bio-physical resources (manure, fodder, draft-power). The score of 100% indicates a full integration, while the score zero (0%) indicates no active crop-livestock integration (Table 5.3) even if a passive integration may take place through free grazing on crop residues and passive release of manure directly on harvested farms. Nevertheless, all the integration terms in this study refers to the active integration.

***(ii) Cop-livestock integration effectiveness***

This was done using the concept of integration effectiveness (IE) adapted from Bénagabou et al. (2013) and based on the three pillars of the integration defined by Landais and Lhoste (1990): coverage of animal traction (CoDPN), coverage of organic manure needs (CoMN) and coverage of fodder needs (CoFN) (Table 5.3).

The coverage of the needs of the two modules (livestock and crop) were said to be effective if the indicator value was greater or equal to hundred percent (IE>=100%), and not effective if the value was lower than hundred percent (IE<100%). The integration effectiveness was considered low when its value was lower than fifty percent (IE<50%) but the values between fifty and hundred percent (50% <=IE<100%) indicated a medium integration.

**(iii) Integration efficiency**

The integration efficiency (IEffi) (Table 5.3) gives an idea on the performance of the integrated system in terms of exchange between livestock and crop modules. It is computed following Tow et al. (2011). For these authors, dealing with efficiency, appropriate output/input ratio was determined, including output per unit of land, labour, fertilizer, solar radiation, support energy, cash input or rainfall. Among these spectrum of efficiency expressions, the current study aims at expressing the concept of integration efficiency as a ratio of the total matter (manure and fodder) gathered (the output) to the labour (gathering efforts of households) needed (the input).

**(iv) Effort of crop-livestock integration**

The Effort of crop-livestock integration is the effort made to cover farm fertility and livestock feed needs. It is computed as the amount of labour needed to cover these needs. This consists of providing an adequate amount of fodder or manure mobilised through composting, hay making, fodder cropping, fodder, or manure transportation. In this perspective, when less or no effort was made to fulfil the integration purpose, and the exchanges (manure, fodder, animal power) among components, thus rather driven solely by livestock in mobility (Bénagabou, 2018), the integration is said to be passive. Two indicators were used to characterise the integration efforts: total integration effort (TIE) and daily integration effort (DIE). The TIE gives a view on the effort deployed by the household members to accomplish all the integration requirements while the DIE gives an idea on the effort deployed on the daily basis.

**(v) Financial crop-livestock integration**

The financial integration is an integration along the ownership dimension. This refers to a stage for a special case of crop–livestock interaction that is largely independent of spatial and temporal integration and the constraints of scale. In this case there is a beneficial exchange of financial resources with no bio-physical interactions (Sumberg, 2003). The current research sought at computing an indicator of this financial integration as a ratio of the amount (USD) raised from livestock activities to the total annual expenditures required for cropping activities and vice-versa. The yearly required amount for cropping (USD/ha) and livestock activities (USD/head) for health and concentrate feed expenditures respectively are indicated in the Table 5.4. The indicator will therefore give an overview on the contribution of each component (Livestock and crop) of the integration to support each other's activities.

Table 5.3: Crop-livestock integration indicators computation

| Basis of computation | Formulas |
|---|---|
| Global level of integration was estimated based on: Number of interaction or resources transfer involved out of the total possible resources: manure, fodder, draft-power and finance | $LI = \frac{Number\ of\ integration\ practices\ adopted}{total\ number\ integration\ practices\ possible} x\,100$ <br> Where, <br> $LI$: a global level of integration based on the fluxes of four resources including manure, fodder, draft-power and financial resources. <br> Five levels are derived for $LI$: : 0% meaning no integration; 25% (1/4) meaning low level of integration; 50-75% (1/2-3/4) meaning a medium level of integration and 100% (4/4) for a full integration. |
| Level of bio-physical integration was estimated based on number of interaction or resources transfer involved out of the total possible bio-physical resources: manure, fodder, and draft-power | $LI_{bio} = \frac{Number\ of\ integration\ practices\ adopted}{total\ number\ of\ bio-physical\ integration\ practices} x\,100$ <br> Where, <br> $LI_{bio}$: Level of integration based on the fluxes of only bio-physical resources including manure, fodder, and draft-power. <br> Four levels are derived for $LI_{bio}$: : 0% meaning no integration; 33% (1/3) meaning low level of integration; 70% (2/3) meaning a medium level of integration and 100% (3/3) for a full integration. |
| Integration effectiveness estimated based on the coverage of manure needs (CoMN), coverage of fodder needs (CoFN) and coverage of draft power needs (CoDPN) | $IE(\%) = 100 \frac{\sum_i^3 CoIN_i}{N\,bio_i}$ |

| | |
|---|---|
| | Where,<br>$IE$ is the indicator of the integration effectiveness<br>$CoIN_i$ is the coverage of farm integration needs including the coverage of organic manure needs ( $CoMN$ ); the coverage of fodder needs ( $CoFN$ ) and the coverage draft-power needs ( $CoDPN$ ).<br>$Nbio$ is the number of bio-physical integration practices adopted including farm ploughing and weeding from animal draft-power; farm fertilisation from livestock manure mobilised and livestock grazing on stocked crop-residues. |
| Coverage of Manure Needs (CoMN) obtained as a ratio of the total production of organic manure to the annual requirement of organic manure | $CoMN(\%)=100\frac{Total\ quantity\ of\ organic\ manure\ used\ (kg)}{2500\ (kg/ha)(area\ cultivated\ (ha))}$ (Bénagabou, 2018)<br><br>Where,<br><br>$CoMN$ : Coverage of Manure Needs (% of 2,500 kg DM/ha/y)<br>2500 kg/ha/year: an annual recommended amount of DM of organic fertilizer per unit cropped area (hectare) (Berger et al., 1987) |
| Coverage of Fodder Needs (CoFN) obtained as a ratio of the total quantity of<br>stored fodder to the annual livestock feed requirements | $CoFN(\%)=100\frac{Total\ quantity\ of\ fodder\ stored\ (kg)}{365(6.25\ kgDM/TLU/day)(Number\ of\ TLU)}$ (Bénagabou, 2018)<br><br>Where,<br>$CoFN$ : Coverage of Fodder Needs (% of 6.5 kg DM/TLU/day) (Boudet, 1984)<br>$DM$ : Dry matter (kg/year)<br>$TLU$ : Tropical Livestock Unit (a livestock weighting 250 kg)<br>$6.25\ kgDM/TLU/day$ : daily recommended standard of 6.25 kg of dry matter of fodder needed to feed Tropical Livestock Unit (Mémento Agronome, 1991) |

| | |
|---|---|
| Coverage of draft power needs (CoDPN) obtained as a ratio of the number of pairs of draught oxen and the total area cultivated by a holding a year | $CoDPN(\%) = 100 \frac{Number\ of\ pair\ of\ oxen\ available}{Cultivated\ area(ha)/5(ha/\ pair\ of\ oxen)}$ (Bénagabou, 2018)<br><br>5 ha/pair of oxen: an annual recommended standard of 5 hectare of cultivated area per annum and per pair of draft oxen (Vall & Bayala, 2007). |
| Integration efficiency obtained as a ratio of the total organic matter yearly mobilised to the total effort involved | $IEffi(kgDM/man.days) = \frac{TDM(kg)}{W(man)WD(days)}$<br><br>Where,<br><br>$IEffi$ : is the integration efficiency that refers to the quantity of organic matter mobilised by a number of workers over a period of working days.<br>$TDM$ : is the total quantity (kg) of manure and fodder mobilised through household labour.<br>$W$ and $WD$ : are the total number of the workers (man) and working days respectively. The workers mobilised during the total working days are contributing to household labour that is the total efforts made by the household to produce (composting), collect, transport, store, spread manure in field or ration livestock' |
| Total Integration Effort (TIE) computed as the total number of workers multiply by number of working days | $TIE(man.days) = (N_{Workers}(mans))(N_{Working-days}(days))$<br><br>Where,<br><br>$TIE$ is total effort of integration (man-days), |

| | |
|---|---|
| | $N_{Workers}$ is the number of workers<br><br>$N_{Working-days}$ is the number of working days |
| Daily Integration Effort (DIE) computed as the ratio of the total number of workers ($N_{workers}$) to the number of working days ($N_{Working\ Days}$) | $DIE(man/day)=\frac{N_{Workers}(man)}{N_{Working\,Days}(day)}$<br><br>Where,<br>$DIE$ is the daily integration effort (workers/day),<br>$N_{Workers}$ the number of workers<br>$N_{Working-days}$ the number of working days |
| Financial integration obtained as the ratio of financial integration needs to the number of financial flux between the integrated system components | $F_{Intg}.(\%)=100\frac{\sum_i^2 CoFN_i}{NFF_i}$<br><br>Where,<br>$F_{Intg}$ is the indicator of the effectiveness of the financial integration<br>$CoFN_i$ is the coverage of financial integration needs including the coverage of cropping financial needs ( $CoCFN$ ) through the purchase of seeds, fertilizer, labour payment; and the coverage of livestock breeding financial needs ( $CoLFN$ ) through feeding and veterinary cost.<br>$NFF_i$ : the number of financial fluxes adopted between cropping and livestock module. |

| | |
|---|---|
| Coverage of crop financial needs | $Co_{CFN}(\%)=100\frac{FRL}{CFN}$<br><br>Where,<br>$FRL$ is the financial resource from livestock redirected by the household to support cropping expenditures,<br>$CFN$ is the cropping financial needs referring to the annual required expenditures for cropping |
| Coverage of livestock financial needs | $Co_{LFN}(\%)=100\frac{FRC}{LFN}$<br><br>Where,<br>$FRC$ is the financial resource from cropping redirected by the household to support livestock breeding expenditures,<br>$LFN$ is livestock financial needs referring to the annual required expenditures for livestock feeding and veterinary costs |

Source: Author's Own Compilation from literature, 2023.

Table 5.4: Livestock and cropping annual required expenditures

| Designations | Cropping (USD/ha/year) | Livestock (USD/head/year) |
|---|---|---|
| Maize | 457.6 | - |
| Sorghum | 278.9 | - |
| Groundnut | 170.6 | - |
| Cowpea | 247.3 | - |
| Millet | 330.2 | - |
| Cotton | 589.6 | - |
| Cattle | - | 1144.0 |
| Sheep | - | 376.9 |
| Goat | - | 376.9 |
| Poultry | - | 7.2 |
| Total | 2074.2 | 1905.0 |

Source: Author's Own Compilation using data from crop and livestock extension services of Niou (Sudan-Sahel), Dano (Sudan) and Dori (Sahel) districts, Burkina Faso, 2023.

#### 5.2.3.3 Relationship between the level of integration, the effectiveness and efficiency

The relationship between the level of integration; effectiveness and efficiency was analysed using the simple linear model. The analysis was performed across the climatic zones.

#### 5.2.3.4 Holistic characterisation of crop-livestock integration across climatic zones

The holistic characterisation of crop-livestock integration was done in each zone using a set of indicators designed along the different integration dimensions (space, time, ownership, and management). This contributes to give a holistic overview on crop-livestock integration pattern and performances across climatic zones and West Africa in general where countries have similar ways and practices in supporting crops and livestock interactions.

#### 5.2.3.5 Statistical analysis

Data were statistically checked to meet the assumptions of normality (Shapiro-Wilk test) and variance homogeneity (Levene test). Graphical analyses (barplots, scatter-plots, and violin-plots) were performed on integration indicators across the three climatic zones. Due to the high dispersion in crop-livestock integration data, these were normalized for the sake of visualization. To compare crop-livestock integration between climatic zones, we performed a one-way analysis of variance (ANOVA). The Tukey's Honest Significant Difference (Tukey HSD) analysis (Tukey, 1949) was performed when significant differences were detected. Alternative non-parametric tests (Kruskal and Wallis, 1952) and Wilcoxon Rank Sum Test (Barros et al., 2018) were carried out when the assumptions of normality and equality of variance of data were not met.

## 5.3 Results and Discussion

### 5.3.1 Crop-livestock integration needs

Across climatic zones of Burkina Faso, there still exists a wide gap between current and required coverage of the integration needs of by most farmers in each zone. The manure needs were effectively covered by only 1.0%, 0.5% and 17.3% of farmers in Dano (Sudan), Niou (Sudan-Sahel) and Dori (Sahel) respectively (Figure 5.5a). The average level of coverage in manure needs, revealed values of (14.0 ± 13.6) %, (23.2 ± 15.0) % and (37.5 ± 27.3) % within Dano (Sudan), Niou (Sudan-Sahel) and Dori (Sahel) respectively (Figure 5.5d).

The highest value of manure needs coverage obtained in the Sahel can be explained by an easy availability and in a greater amount of manure in this zone that is typically a zone of livestock rearing as the main activity. Farmers can therefore have access to manure with less effort to do unlike manure mobilisation through the composting as practised in the Sudan and Sudan-Sahel zones. The composting practice which is a highly water and biomass consuming practice is easily conducted by farmers in Sudan than in Sudan-Sahel zone. Coupled to a relative higher water availability, non grazed crops residues are sustaining the composting in Sudan. Sudan-Sahel, being the transition zone, is a water-scarce environment with poor availability of natural vegetation from grazing lands. Crop residues occupied in this case a greater place in herd feeding strategies than in compositing (Figure 5.5d,e). Soils fertilisation from livestock relies more heavily on livestock dungs collection on grazing lands and around livestock watering points.

Fodder needs were effectively covered only by 0.5 %, 10.5 % and 29.6 % of farmers' households in Sudan, Sahel and Sudan-Sahel respectively (Figure 5.5b). The average level of (9.73±9.71) %, (42.2±34.5)% and (71.02±46.8)% were obtained for the coverage of fodder needs within Sudan, Sahel and Sudan-Sahel zones respectively (Figure 5.5e). Farmers in the Sahel and transition zone (Sudan-Sahel) characterized by poor grazing lands, have to make more efforts in crop-residues collection and storage for feeding during dry seasons where grazing can no longer provide enough feeds to support herd needs. This justifies the highest average values in the coverage of fodder needs in these zones compared to the Sudan zone.

Finally, the draft power needs were effectively covered by 36.9 %, 0.0% and 26.1% of farmers in Sudan, Sahel and Sudan-Sahel zone respectively (Figure 5.5c). Average values of (138.9±90.6) %, and (80.5±49.4)% were obtained for the coverage of draft power needs within Sudan and Sudan-Sahel respectively (Figure 5.5f). On average, the draft-power needs were effectively covered only in the Sudan zone (Figure 5.5f). The essence of the results indicates that to cultivate larger farms sizes for both staple and cash crops (cotton (*Gossipium hirsutum*) for example) there is a need for power. This power is provided mainly by animals within Sudan and Sudan-Sahel. Unlike these zones, the Sahel zone has less use of animal power for cropping; when it is used this relies mainly more on donkey for transportation and seldom for cultivation. That may be explained by several factors including both sociological and technical aspects. Most of the soils in the Sahel zones are sandy soils and ploughing are most of the time avoided. In addition, farm size are generally smaller and farmers household can easily support the labour needed for cropping. Moreover, sociologically there is a usual reluctance of Fulani farmers (dominant in the Sahel zone) towards the use of draft oxen to cultivate or plough their fields (Boutrais, 2000). Fulani are said to have such a close connection with cattle that they are less inclined to use oxen for cultivation. This could explain the absence of draft power from the interviewed households even if a seldom use of draft-power exists in the Sahel region according to agriculture extension services.

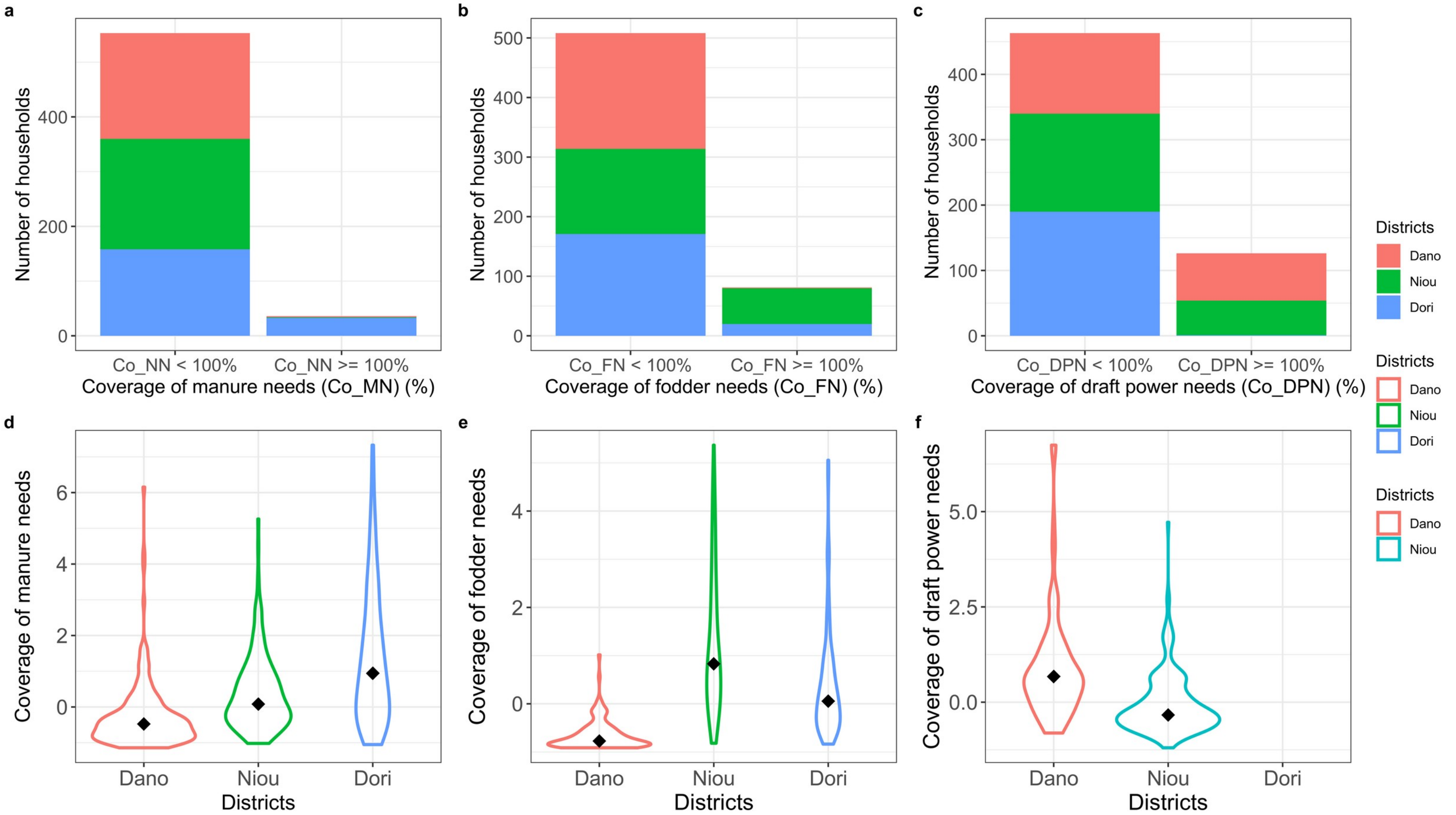


Figure 5.5: Coverage of crop-livestock integration needs. (a) number of households by the level of coverage of manure needs; (b) number of households by the level of coverage of fodder needs; (c) number of households by the level of coverage of draft power needs; (d), (e) and (f) average values of the coverage of manure, fodder and draft-power needs respectively. ♦: median value. The violin plot values are standardized values of the original data. Source: Author's Own computation, 2023.

### 5.3.2 Level and effective integration by farmers

The level of crop-livestock integration by farmers was significantly different between the three climatic zones ($p<0.05$). A greater number of farmers (91.6%) in the Sahel (Dori) have adopted full integration and differed significantly from the Sudan-Sahel (Niou) and the Sudan zone (Dano) where 62.3% and 48.2% of interviewed farmers have adopted full integration respectively. Only, medium level of integration (50% to 75%) and full integration (100%) were characteristic of the Sudan-Sahel and Sahel zones. Inversely, farmers in Sudan revealed all the level of integration from lower (25%) to full (100%) (Figure 5.6a). It seems that as we move from the Sudan through the Sudan-Sahel to the Sahel zones (along a climatic gradient) farmers are more prone to adopt full integration to cope with the harsh environment in their livelihoods strategies while there are less prone to go for full integration in the Sudan zone characterised by a more favourable environmental condition.

Crop-livestock integration was effective for a very few farmers' households across climatic zones. Only 5.1%, 10.5% and 14.8% of households revealed an effective ($IE>=100\%$) crop-livestock integration within Sudan, Sahel and Sudan-Sahel zones respectively (Figure 5.6b). Medium level of effectiveness ($50\%<=IE<100\%$) was experienced by 19.0%, 28.8% and 48.3% of farmers in Sudan, Sahel and Sudan-Sahel zones respectively (Figure 5.6c). Finally, the lowest level of effectiveness ($IE<50\%$) were experienced by the majority of the interviewed farmers in Sudan (75.9%) and Sahel (60.7%) zones compared to Sudan-Sahel zone (36.9%) (Figure 5.6d). Similarly, to the level of integration, crop-livestock integration was found comparatively more effective in the Sudan-Sahel and Sahel zones than the Sudan zone. This is a way for farmers in the harsh environment to be more resilient to chocks like climate change. If the farmers in such harsh environment are compelled to take advantage of CLI as resilience strategy, those in the Sudan, despite the relative favourable conditions should also improve in the adoption of this practice for sustainable land use and the related resources. Indeed, the improvement of CLI in the Sudan zone might reduce livestock pressure on natural vegetation biomass and diversity. Soil fertility could be enhanced through organic fertilisation and preserved from degradation from systematic use of chemical fertilizers to maintain fertility.

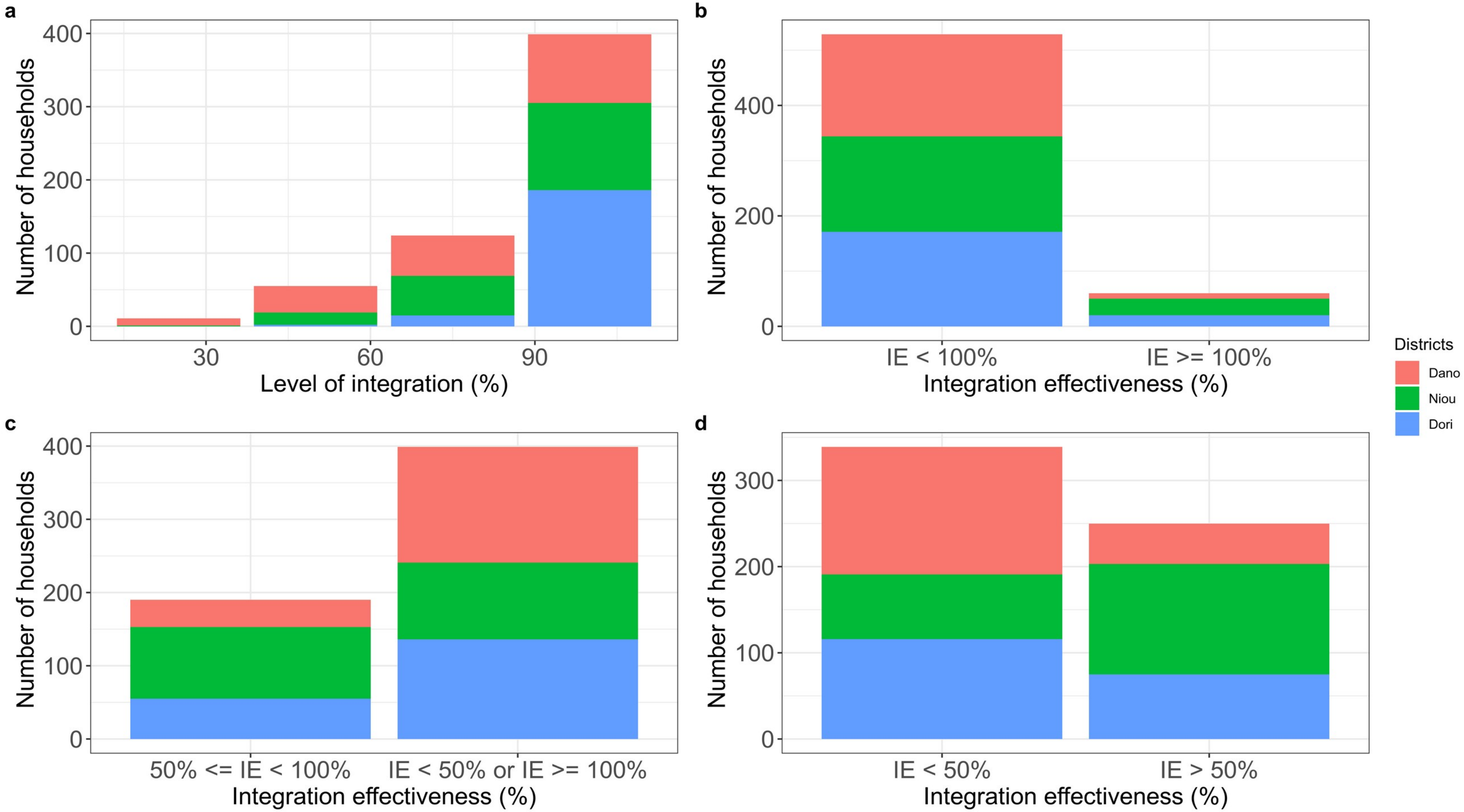


Figure 5.6: Level and effectiveness of crop-livestock integration across climatic zones of Burkina Faso. (a) Number of households by level of integration; (b-d) Number of household by level of integration effectiveness (IE). Source: Author's Own computation, 2023.

#### 5.3.2.1 Level, efforts, effectiveness and integration efficiency

***Level of crop-livestock integration***

The highest global level of integration (LI) (97.7 ± 8.1) % is being experienced in the Sudan-Sahel zone (Niou) and significantly differed from that experienced in the Sahel zone (Dori) (88.1 ± 17.0) % and the Sudan zone (Dano) (79.9 ± 22.9) % (Figure 5.7a). The level of bio-physical integration account similarly the highest values for Sudan-Sahel (99.5±4.0) % and Sahel (91.6 ± 15.7) % and against a relatively low level in Sudan (77.4±26.7) % (Figure 5.7b). The closeness of the two categories of the level of integration indicates that financial resources flux has a relatively low contribution into the global level of integration (LI). However, this financial flux should not be neglected as it is sustaining the integrated crop-livestock system beyond the bio-physical aspect. When this flux takes place, it contributes mainly in providing cropping inputs (fertilizer, seeds, ploughing service etc.) and also contribute into livestock health, feeds costs and finally to herds size reconstitution mainly through small ruminants.

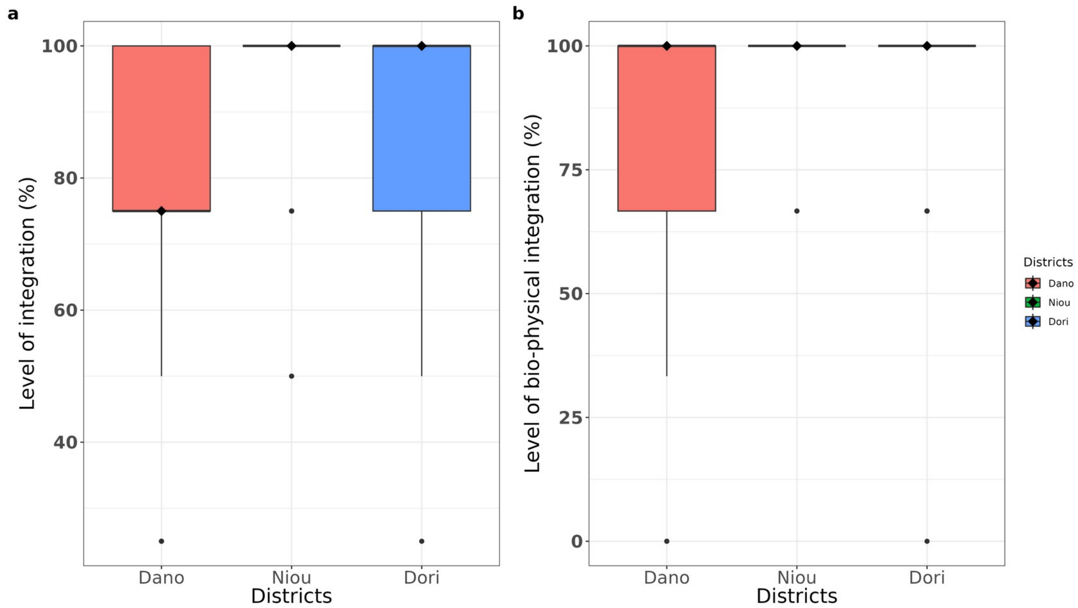

Figure 5.7: Crop-livestock level of integration. (a) global level of integration; (b) level of bio-physical integration. ♦: median value. Source: Author's Own computation, 2023.

### *Crop-livestock integration efforts*

The active integration was described through the analysis of the total integration effort (TIE) and the daily integration effort (DIE) computed based on the number of workers involved and the duration of working days needed to ensure integration. TIE increases from the Sahel (Dori) (261.5±199.6 man-days); Sudan (Dano) (277.8±272.5 man-days) and finally Sudan-Sahel (Niou) (675.2±375.2 man-days) (Figure 5.8). Inversely the DIE was found rather higher in Sudan (7.4±6.7 man/day) than in Sahel (1.05±1.0 man/day) and Sudan-Sahel (2.5±1.7 man/day) (Figure 5.8). This indicates that on the daily basis the effort is more intense in the Sudan zone where shorter period (3.0±2.2 months) are reserved to the integration activities compared to the Sahel (5.0±3 months) and the Sudan-Sahel (6.0±2.2 months) zones. The DIE being the ratio of the number of workers to the working days duration, this justify the highest value in the Sudan zone compared to the two other zones, even if the overall effort (at both monthly and yearly scales) is lower in this zone than in Sudan-Sahel zone. The logic behind is that efforts in the Sudan zone (shorter working period (3 months) and medium size of workers (18.9±13.8 people)), are mainly made for manure mobilisation through pit composting that need high labour and few for fodder collection and storage but generally over a short period. On the contrary in Sudan-Sahel zone very high labour (longer working period (6 months) and maximum number of workers (21.2±9.3 people)) are needed to ensure the mobilisation of both fodder and manure through a seldom but labour-intensive pit-composting. Finally, in the Sahel zone a long enough period (5 months) with a relative lower number of workers (7.9±5.7 people) are needed to mobilize mainly fodder and relatively few labour for manure mobilisation (transportation mainly and very little pit composting).

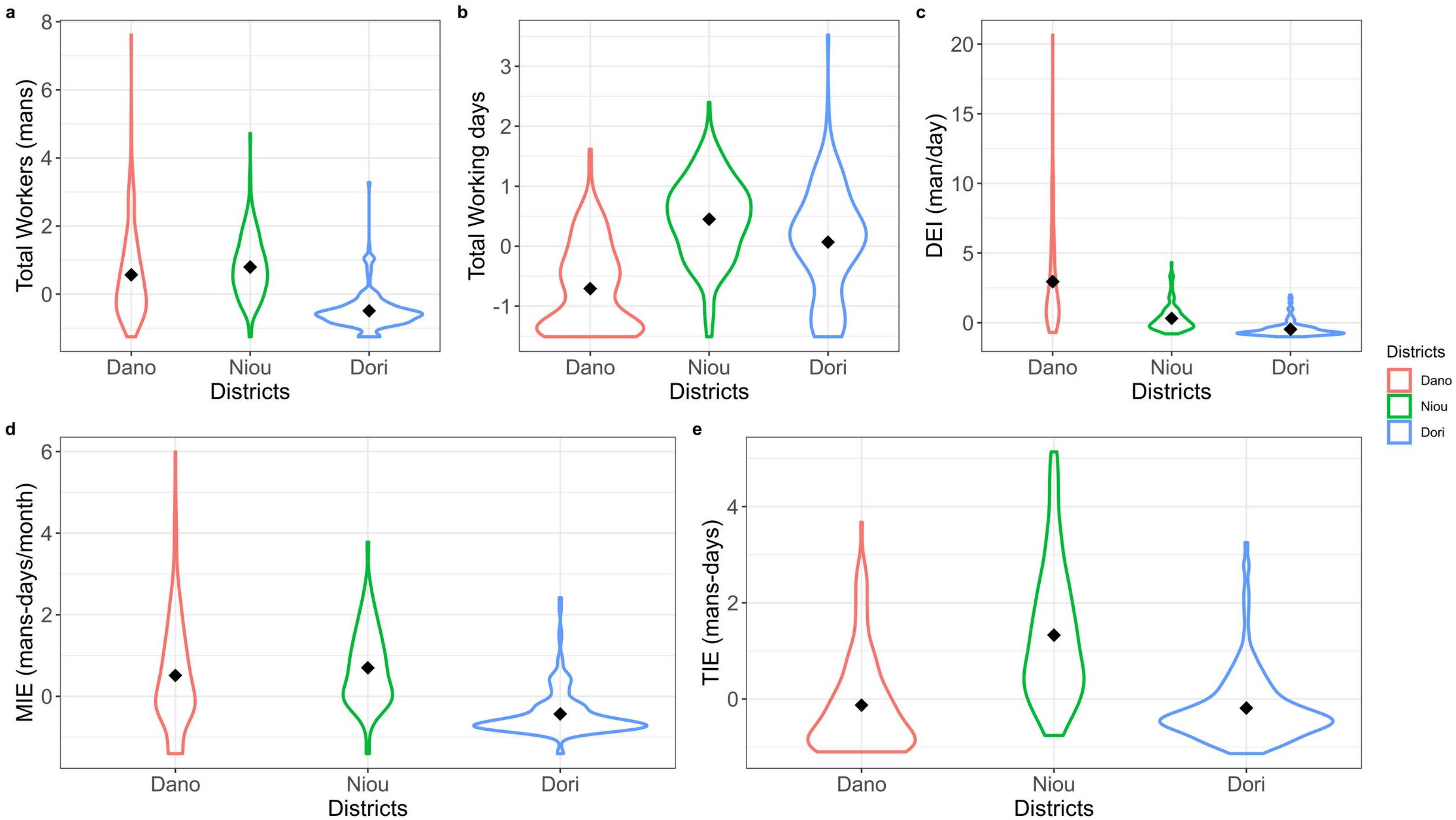


Figure 5.8: Crop-livestock integration efforts. (a) number of workers; (b) number of working days; (c) daily integration effort (DIE); (d) monthly integration effort (MIE); (e) total integration effort (TIE); ♦: median value. The plot values are standardized values of the original data. Source: Author's Own computation, 2023.

***Integration effectiveness and efficiency***

Overall, all the zones revealed both a low integration effectiveness and efficiency meaning that the interaction between crop and livestock needs considerable improvement (Figure 5.9). As indicated in previous literature (Martin et al., 2016; Moraine et al., 2014; Peyraud et al., 2014; Ryschawy et al., 2017), the reason of this underperformance is related to the limited farm workforce of some farmers, resources (water for composting, equipment) and skills required for an effective and efficient crop-livestock-integration.

On average crop-livestock integration was comparatively more effective in the Sudan-Sahel zone (65.9 ± 32.0) % followed by Sahel zone (44.9 ± 29.5) % and Sudan zone (35.6 ± 35.0) % ($p<0.05$). This is explained by the peculiar nature of the two extreme zones (Sudan and Sahel) for crop or livestock production respectively, compared to the transition zone. This situation could limit crop-livestock interactions once a farming system becomes entrenched (Ryschawy et al., 2017). Allowing and supporting resource exchanges between farmers could be an effective alternative to overcome farm level limitations to crop-livestock integration (Lemaire et al., 2013a; Martin et al., 2016; Moraine et al., 2016a, 2016b, 2014; Ryschawy et al., 2017). Crop-livestock integration in the transition zone was less efficient (13.7 ± 12.0 kg DM/man.day) than in Sudan (18.4 ± 17.9 kg DM/man.day) and Sahel zone (33.2 ± 25.5 kg DM/man.day) respectively. This situation is explained by the fact that the transition zone does not have the same advantages of both Sudan and Sahel in terms of pasture and manure availability. Farmers within such zones must therefore make additional efforts to adapt to their environmental conditions to fulfil the purpose of integration (effort to produce, collect, transport, store, feed livestock or spread manure on the fields). That explains rather the highest average level of effectiveness reached in Sudan-Sahel zone compared to the two other zones.

This situation relies on a comparatively less effort (87.1 ± 82.0 man-days) made by Sahel (Dori) and Sudan (Dano) (58.8 ± 57.8 man-days) farmers to gather manure, unlike Sudan-Sahel farmers (259.3 ± 248.1 man-days). This situation can be explained by the fact that manure in the Sahel zone is comparatively highly accessible to farmers and constitutes the highest contribution in soil fertilitilisation strategies ahead of chemical fertilizers (NPK and Urea). Furthermore, the lowest mobilisation of manure in Sudan zone behind the Sudan-Sahel zone can be explained by the strong utilisation of chemical fertilizers by farmers among majority of cotton (*Gossipium hirsutum)* farmers. These farmers unlike Sudan-Sahel (non-coton zone) have alternative of chemical fertilisation in soil fertility maintenance.

Similarly, unlike the Sudan-Sahel zone (448.1 ± 357.7 man-days) comparatively less effort is made in the Sudan zone (280.4 ± 261.7 man-days) and Sahel zone (181.8 ± 178.1 man-days) in crop residue collection and storage. This situation could be due to high availability of pasture from natural vegetation and considerable quantity of non-collected crop-residues in the Sudan zone on which livestock freely graze during a longer period of the year (October/November to May/June). Moreover, the lowest effort in the Sahel compared to Sudan and Sudan-Sahel could be due to a constraint of pasture availability on farm beyond three (3) months after harvest.

In a nutshell, farmers in the transition zone (Sudan-Sahel zone), do not benefit from the environmental advantages of the two others (comparatively higher availability of manure and fodder for farmers uses in the Sahel and Sudan zones respectively). They have therefore to make additional efforts to mobilise both fodder and manure to sustain their production systems in the context of climate change and where prices of both concentrate feed and mineral fertilizer are on the increase.

Overall, the findings indicated that at this stage of crop-livestock integration across climatic zones of Burkina Faso, much more remains to be done to enhance the potential of this productive and sustainable farming strategy recommended by several researchers (Bénagabou, 2018; Rasambatra et al., 2020; Rufino et al., 2009; Vall et al., 2017). This situation was similarly reported in the Sudan zone of Burkina Faso by Vall et al. (2006), who indicated that resource exchanges between agriculture and livestock are progressing among agro-pastoralists, farmers, and breeders, but can still be improved.

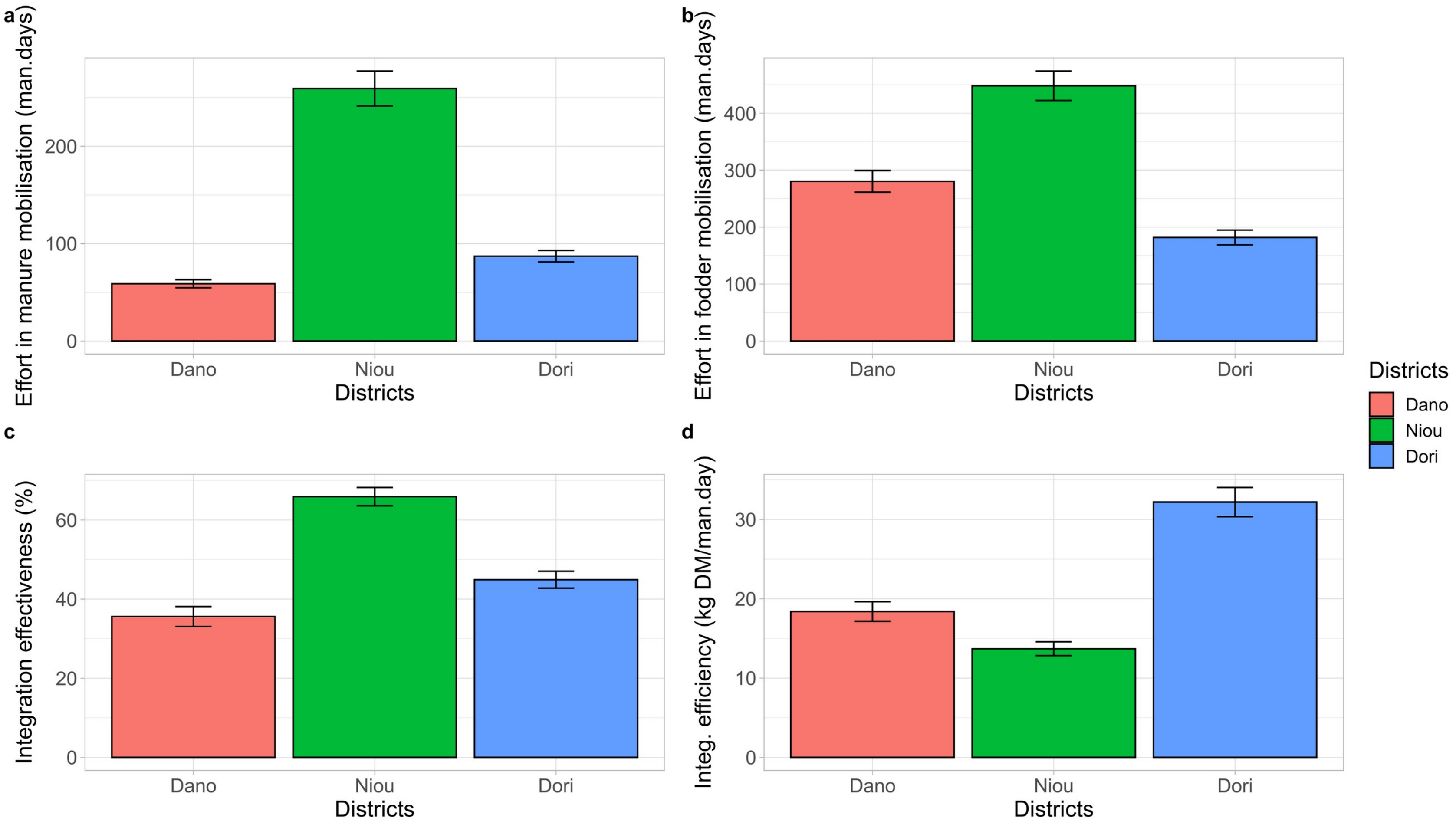

Figure 5.9: Crop-livestock integration across climatic zones. (a) (b) Efforts in mobilisation of manure and fodder; (c) Integration effectiveness and (d) Integration efficiency. Source: Author's Own computation, 2023.

**Integration in term of financial resource exchanges**

Beyond the bio-physical resource exchanges in crop-livestock interactions, financial resources play an important role in these interactions. Previous literature (Sumberg, 2003) on crop-livestock integration has not sufficiently investigated the financial aspect of the integration, considered important across climatic zones of Burkina Faso. This study included a more complete characterisation of integration along the space (for crop residue and manure), time (for power, crop residue and financial resources), ownership (for financial resources) and management dimension, involving exchanges along the other dimensions. The financial resource exchange or financial integration is resulting from the coverage of both cropping and livestock financial needs using financial resources from each component (crop and livestock). The overall financial integration and the coverage of livestock financial needs from cropping was very weak and not significantly different between climatic zones (Table 5.5). Inversely, the coverage of cropping financial needs from livestock component were significantly different among climatic zones ($p<0.05$). It appears that livestock is supporting more the cropping component in the Sahel (59.5 % vs 40.5 %) and Sudan-Sahel (57.0 % vs 43.0 %) zones. Inversely, in the Sudan zone it is cropping component that is supporting livestock component (50.7 % vs 49.3 %). Overall, livestock component (55 %) is supporting more the cropping component (45 %).

In terms of financial resources used by farmers to cover cropping and livestock breeding needs, the highest coverage of cropping financial needs (CoCFN) (ie costs for seeds, fertilizers, and workforce...) from livestock outputs, is experienced in the Sudan-Sahel zone (9.8±6.1 %) followed by Sudan zone (7.4±7.0 %) and then the

Sahel zone (3.5±3.5 %) (Figure 5.10). Inversely, the highest coverage of livestock financial needs (CoLFN) (i.e health and feeds costs) from cropping outputs, have been experienced in the Sahel (0.7±0.6 %) followed by the Sudan zone (0.5±0.5 %) and the Sudan-Sahel zone (0.4±0.3 %). Finally, the overall financial integration is comparatively higher (7.3±5.6 %) in the Sudan-Sahel than the two extremes zones (Sudan (3.6±3.6 %) and Sahel (2.8±2.7 %)). It appears that the pattern of financial integration performance across zones aligned with that of the bio-physical integration characterised by higher effectiveness in the Sudan-Sahel. It can be concluded that there is a comparatively higher persistence of farmers in the transition zone to involve themselves by all means (physical and finance) into the integration. Although, the financial integration is revealing lower percentages across zones, this should not be neglected, because it can play an important role of livelihood protection in the face of different risks. These risks, constituting significant threats to agricultural production (crops and livestock), could include drought, floods, locust invasion, pests and diseases, etc. Indeed, in cases of crop failure, livestock component can support the resilience of cropping. This could be done by buying fertilizers, seeds, pesticides, and covering the cost of hiring labour (workers, draft oxen, etc.). Similarly, in a given year, in the event of a decline in animal production due to livestock disease outbreaks and other induced climate-related impacts, this component may be supported to withstand the adverse effects of risks. Thus, the financial resources from crops could help farmers to reconstitute their herds, to have more animal feed and a healthier herd for new production cycles.

Table 5.5: Financial resource flux between livestock and crop component along ownership and management dimension

| Zones | Financial resources fluxes | Frequency (%) |
|---|---|---|
| Sudan (Dano) | Livestock revenue spent in agriculture | 49.3 |
| | Agriculture revenue spent in livestock activities | 50.7 |
| Sudan-Sahel (Niou) | Livestock revenue spent in agriculture | 57.0 |
| | Agriculture revenue spent in livestock activities | 43.0 |
| Sahel (Dori) | Livestock revenue spent in agriculture | 59.5 |
| | Agriculture revenue spent in livestock activities | 40.5 |
| Total | Livestock revenue spent in agriculture | 55.0 |
| | Agriculture revenue spent in livestock activities | 45.0 |

Source: Author's Own computation, 2023.

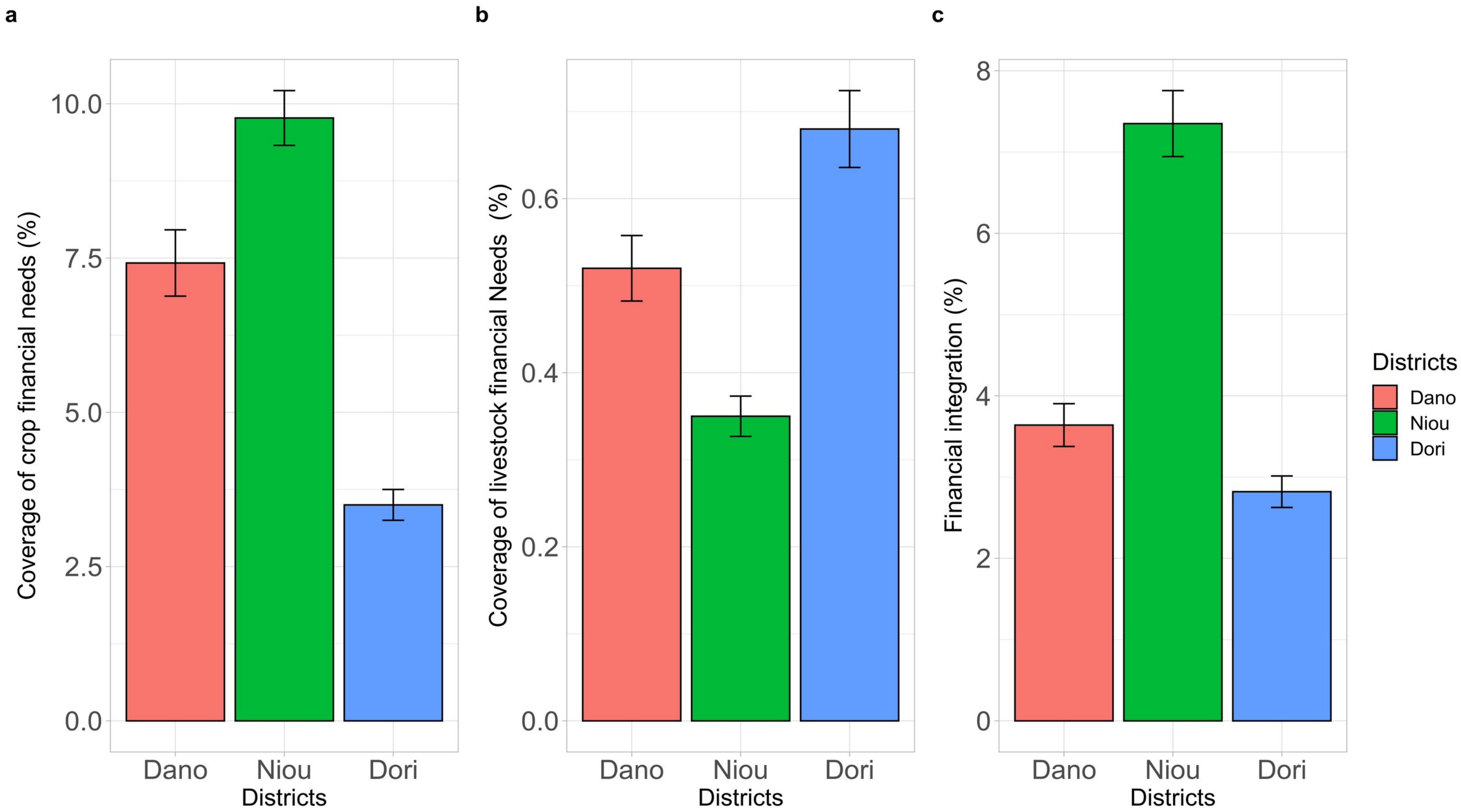


Figure 5.10: Financial crop-livestock integration across climatic zones of Burkina Faso. (a) coverage of cropping financial needs; (b) coverage of livestock financial needs; (c) financial integration. Source: Author's Own computation, 2023.

### 5.3.3 Relationship between the level of integration, effectiveness and efficiency

The relationship between the integration effectiveness, efficiency and the level of integration showed a different pattern across the climatic zones. The integration effectiveness was positively and significantly predicted by the level of integration in the Sudan zone ($R^2adj = 0.26$, slope = 0.79, p-value = $2.72e^{-14}$) (Figure 5.11a). Thus, in this zone, the more the integration, the more its effectiveness. Unlike this zone, the level of integration did not significantly associate with effectiveness in Sudan-Sahel and Sahel zone (Figure 5.11d and 5.11g). This could be explained by the fact that in the Sudan zone there is a more favourable environment for an effective performance of integration practices. On the contrary, within the harsh environments (Sudan-Sahel and Sahel zones), the effectiveness of integration practices could be stemmed even with a full level of integration. The integration efficiency showed no significant association with the level of integration in all climatic zones ($p<0.05$) (Figure 5.12b, 5.11e and 5.11h). Thus, an increasing level of integration is not necessarily implying improved efficiency. This could be explained by the fact that the draft-power dimension could not be captured in the integration efficiency but rather based on matter transfer (manure and fodder). Finally, the efficiency and the effectiveness were rather positively correlated in the Sudan-Sahel ($R^2adj = 0.12$, slope = 0.13, p-value = $4.66e^{-07}$) (Figure 5.11f) and Sahel ($R^2adj = 0.065$, slope = 0.25, p-value = $4.69e^{-04}$) zones (Figure 5.11i) but no significant association was found between these two indicators in the Sudan zone ($p<0.05$) (Figure 5.11c). Thus, it appears that within the harsh environments (Sudan-Sahel and Sahel), the integration effectiveness also implies its efficiency with regards to matter (manure and fodder) mobilisation. This means that farmers in such environments that performed effective integration are those who efficiently mobilised manure and fodder.

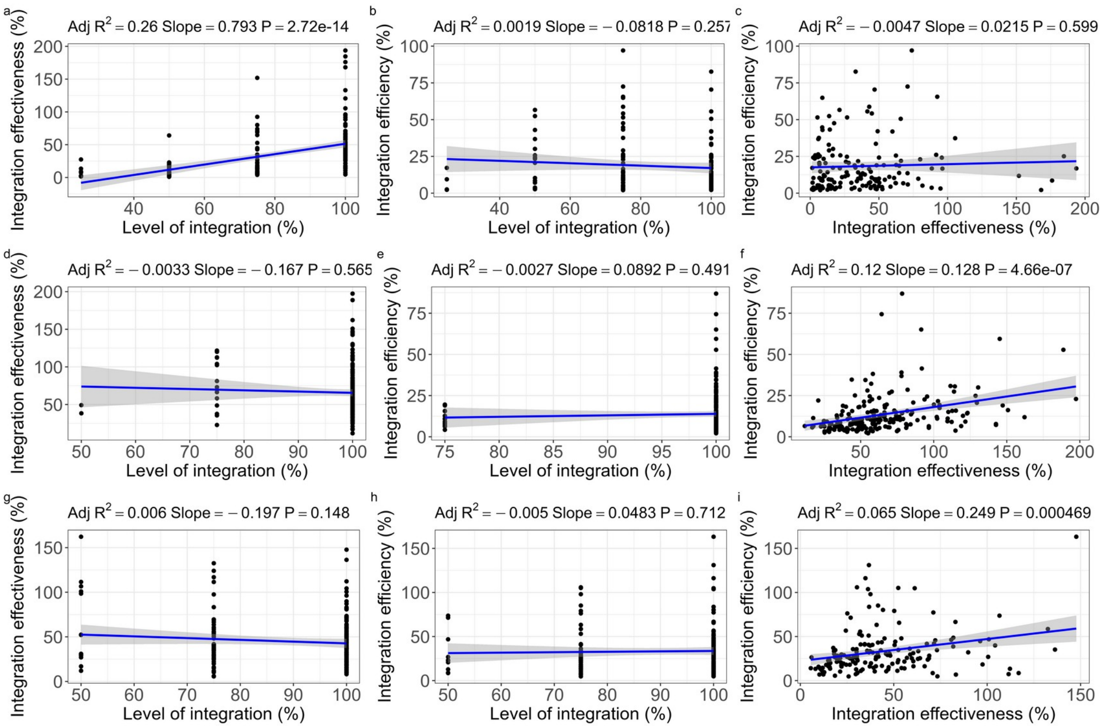


Figure 5.11: Relationship between the level of integration, integration effectiveness and efficiency at district scale. (a), (b) and (c) indicate relationship in Dano district (Sudan zone), (d), (e) and (f) indicate relationship in Niou (Sudan-Sahel zone);(g), (h) and (i) indicates relationship in the Sahel zone. Source: Author's Own computation, 2023.

### 5.3.4 Holistic overview on crop-livestock integration

The findings of the current research can allow a more holistic description of crop-livestock integration. This adds more description to the categorisation of crop-livestock integration along the integration dimensions described by Sumberg (2003). Beyond the author's findings, this work has linked crop-livestock integration dimensions to its levels and effectiveness for a comprehensive view of this mixed-crop-livestock farming system in Burkina Faso and across West-Africa in general

(Table 5.6). It appears that across climatic zones, crop-livestock integration evolves from a low through medium to full level and effective integration. The low, medium and full levels of integration and effectiveness, depended on levels of exchanges of resources (manure, fodder, traction, finance) among crop and livestock modules. Resources exchanges take place along space, time, ownership, and management dimensions. Therefore, three possible combinations of the integration effectiveness (IE) (IE<50 %, 50 %<=IE<100 %, IE>100 %) can be associated with four possible levels of integration (20 %, 50 %, 75 % and 100 %). Each combination is also associated with resource transfer between livestock and crop modules (Table 5.6).

Table 5.6: Holistic description of crop-livestock integration across climatic zones

| Integration dimensions | | | | LI (%) | IE (%) | Exchanges | Descriptions of the level and the effectiveness of crop-livestock integration |
|---|---|---|---|---|---|---|---|
| Space | Time | O | M | | | | |
| 1 | 1 | 1 | 1 | 100 | >=100<br>50<=IE<100<br>IE<50 | Manure, fodder, draft power and financial resources | Full and effective<br>Full and medium effectiveness<br>Full and low effectiveness |
| 1 | 1 | 0 | 1 | 75 | >=100<br>50<=IE<100<br>IE<50 | Manure, fodder, draft power | Medium level and effective<br>Medium level and medium effectiveness<br>Medium level and low effectiveness |
| 1 | 1 | 1 | 1 | 75 | >=100<br>50<=IE<100<br>IE<50 | Manure, fodder, financial resources | Medium level and effective<br>Medium level and medium effectiveness<br>Medium level and low effectiveness |
| 1 | 1 | 1 | 1 | 75 | >=100<br>50<=IE<100<br>IE<50 | Manure, draft power, financial resources | Medium level and effective<br>Medium level and medium effectiveness<br>Medium level and low effectiveness |
| 1 | 1 | 1 | 1 | 75 | >=100<br>50<=IE<100<br>IE<50 | Fodder, draft power, financial resources | Medium level and effective<br>Medium level and medium effectiveness<br>Medium level and low effectiveness |
| 1 | 1 | 0 | 0 | 50 | >=100<br>50<=IE<100<br>IE<50 | Manure, fodder | Medium level and effective<br>Medium level and medium effectiveness<br>Medium level and low effectiveness |
| 1 | 1 | 0 | 0 | 0 | >=100<br>50<=IE<100<br>IE<50 | Manure, draft-power | Medium level and effective<br>Medium level and medium effectiveness<br>Medium level and low effectiveness |
| | | | | | >=100 | | Medium level and effective |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 50 | 50<=IE<100 | Manure, financial resources | Medium level and medium effectiveness |
| | | | | | IE<50 | | Medium level and low effectiveness |
| | | | | | >=100 | | Medium level and low effectiveness |
| 1 | 1 | 1 | 1 | 50 | 50<=IE<100 | Fodder, financial resources | Medium level and medium effectiveness |
| | | | | | IE<50 | | Medium level and low effectiveness |
| | | | | | >=100 | | Medium level and effective |
| 1 | 1 | 0 | 0 | 50 | 50<=IE<100 | Fodder, draft power | Medium level and medium effectiveness |
| | | | | | IE<50 | | Medium level and low effectiveness |
| | | | | | >=100 | | Medium level and effective |
| 1 | 1 | 1 | 1 | 50 | 50<=IE<100 | Draft power, financial resources | Medium level and medium effectiveness |
| | | | | | IE<50 | | Medium level and low effectiveness |
| | | | | | >=100 | | Low level but effective |
| 1 | 1 | 0 | 0 | 25 | 50<=IE<100 | Manure | Low level and medium effectiveness |
| | | | | | IE<50 | | Low level and low effectiveness |
| | | | | | >=100 | | Low level but effective |
| 1 | 1 | 0 | 0 | 25 | 50<=IE<100 | Fodder | Low level and medium effectiveness |
| | | | | | IE<50 | | Low level and low effectiveness |
| | | | | | >=100 | | Low level but effective |
| 1 | 1 | 0 | 0 | 25 | 50<=IE<100 | Draft power | Low level and medium effectiveness |
| | | | | | IE<50 | | Low level and low effectiveness |
| | | | | | >=100 | | Low level but effective |
| 0 | 0 | 1 | 1 | 25 | 50<=IE<100 | Financial resources | Low level and medium effectiveness |
| | | | | | IE<50 | | Low level and low effectiveness |

LI : level of integration (%); IE : integration effectiveness (%); O : ownership dimension, M: management dimension; CLI : crop-livestock integration; the values of 1 means integration along the dimensions and 0 means no integration. Source: Author’s Own compilation, 2023.

## 5.4 Conclusion

Worldwide, crop-livestock integration is adopted as a smart agricultural strategy to support both the production and sustainability. The findings of this study indicated a distinction between the level of integration and the integration effectiveness. The level of integration referred to the number of crop-livestock interactions in terms of crop-residues, manure, draft-power and financial resources exchanges. The integration effectiveness referred to the level at which the integration benefits are obtained including bio-physical benefits (i.e effective coverage of manure, fodder, draft power needs) and financial benefits (i.e effective coverage of cropping or livestock financial needs). In other words, it referred to the degree at which the *raison d'être* of crop-livestock integration is fulfilled.

The highest level of integration and highest integration effectiveness were experienced in the Sudan-Sahel zone followed by the Sahel and Sudan zones. Inversely, the efficiency was found to be the lowest in the Sudan-Sahel zone due to the higher efforts made by farmers in this transition zone compared to the two other zones. Sudan-Sahel zone is a transition zone that does not benefit from the advantages in terms of fodder availability/accessibility from natural vegetation and non-harvested crop residues in the Sudan zone and of manure availability/accessibility in the Sahel zone.

Very few farmers across the climatic zones realised an effective integration (IE greater or equal to 100 %). This could be due to many factors, including skills, labour and resources (water for composting, equipment). Likewise, the benefits derived from the integration might not be fulfilled, in terms of soil fertility and livestock feeding. This indicates that CLI is not judiciously implemented across climatic zones. This practice can be potentially improved in each zone through more efforts toward crop residues and manure mobilisation and increased draft power utilisation in all zones. This effort must be sustained by policy makers through actions including provision of equipment, training, sensitisation and popularisation of the integration practices.

In conclusion, the described crop-livestock indicators provide an opportunity for a holistic description of crop-livestock integration along space, time, ownership and management dimensions. The work gives more insights for informed decision making by policies makers.

# CHAPTER 6: INFLUENCE OF INTEGRATED CROP-LIVESTOCK SYSTEM ON WATER PRODUCTIVITY, GREENHOUSE GASES EMISSION AND SEQUESTRATION


## ABSTRACT

Farmers' livelihoods in West Africa and in Burkina Faso in particular, have experienced unprecedented adverse impacts of climate change through soil fertility decline, crop failure and a decrease in livestock production. Crop-livestock integration (CLI) is seen as one of the interventions that can contribute to climate mitigation and adaptation efforts. The aim of this study was to investigate the implications of CLI on farming systems emissions, sequestration potential, productivity, and soil fertility. Pearson correlation analysis was conducted to establish relationships between integration indicators and water productivity, carbon dioxide equivalent emission, plants and soils sequestration, plant diversity and soil nutrient contents. Overall, a positive association was achieved between integration indicators and farm emissions, productivity, biodiversity, and soil nutrients. CLI is a tree-based system offering also high sequestration potential that could significantly counterbalance the systems’ emission. However, the coverage of fodder needs negatively associated with soils nutrients content indicating field nutrient mining through crop-residues collection. This therefore requires an appropriate scheme of nutrient return to the soils in the form of manure. CLI therefore offers a framework of nutrient recycling loop between soil, herd, and crops/tree biomass. This is essential for the system's sustainability and the reduction of its reliance on inorganic

fertilizers. CLI is deemed to offer an opportunity to build more resilient farmers and farming systems in Burkina Faso in the face of changing climate.

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Key words: Crop-livestock integration, greenhouse gases, sequestration, water productivity, soils.

## 6.1 Introduction

One of the worldwide challenges threatening human life and its environment is climate change that is likely to remain a worrying phenomenon for the coming decades. Sahel agriculture is highly vulnerable to climate change. It adversely reduces land suitability for cropping and grazing, depletes water, and increases the vulnerability of people (Amole et al., 2021). Mitigating and adapting efforts to face the changing climate is central in the current global environmental debate. Yet, reducing deforestation and carbon emissions from tropical land-use change constitute some of the foremost challenges to sustaining biodiversity and mitigating global climate change (Baccini et al., 2017; FAO, 2020; Houghton and Nassikas, 2017; Rahman et al., 2017). Direct benefits of climate change mitigation and adaptation could be the reduction in change trends and climate-induced impacts. Such efforts are needed in Sub-Saharan Africa (SSA), where the increasing population has led to the expansion of agricultural lands, ecosystem degradation and carbon emissions. The general increase in food demand coupled with agricultural lands expansion and increased use of synthetic fertilizer are the major factors of rapid growth in GHGs emissions (Tilman et al., 2011; Tongwane and Moeletsi, 2018). Indeed, in developing countries, the agricultural sector is a leading contributor to greenhouse gas ($CO_2$, $CH_4$, $N_2O$, chlorofluorocarbons etc) emissions (Tubiello et al., 2015) through both livestock husbandry and cropping. In West Africa, these emissions represent 20 % of the total global emissions, while the continent's average emission increases at an annual growth rate of 2.9 % (Tongwane and Moeletsi, 2018), with a production of cereal crops having the biggest share of the total emissions (Tongwane et al., 2016). Enteric fermentation is the largest source of emissions (Tang et al., 2018; Thamo et al., 2013), with more than half of the total agricultural emissions of the continent (Tongwane and Moeletsi, 2018). Enteric fermentation emissions grew rapidly in Africa between 2000 and 2010 (2.4 % /year) (Smith et al., 2014). This is expected to increase further in the coming decades mainly as a result of low feed quality fed to livestock as well as increasing livestock herd size.

Despite the considerable amount of greenhouse gas emissions from agriculture, there are still uncertainties related to their quantification within developing countries, particularly in SSA (Boateng et al., 2017; Kim et al., 2016; Tongwane and Moeletsi, 2018; Zhu et al., 2016). One of the limitations in emissions estimation is the use of emission factors calibrated with respect to temperate conditions that could lead to emission under or over-estimation in tropical conditions (Boateng et al., 2017). Emission uncertainties make adopting adequate mitigation options in the agricultural sector difficult. Therefore, the global efforts to cut down greenhouse gases could be stemmed in the context of country-specific nationally determined contributions (NDCs). In this perspective Tongwane and Moeletsi (2018) indicated the need for focused research to overcome the large uncertainties associated with greenhouse gas emissions from Africa so that appropriate mitigation plans could be developed.

Nevertheless, despite the unavailability of some emission factors calibrated for tropical conditions, it is still necessary to estimate greenhouse gases emission across SSA countries. Indeed, information on GHGs emission potential from agriculture are essential for state mitigation plan that is still poorly elaborated in Burkina Faso. In this regard, in line with Tongwane and Moeletsi (2018), greenhouse gas mitigation from the agricultural sector should be done more holistically to ensure food security and economic growth in a sustainable way. Mixed-crop-livestock system could be a climate-smart option to this end.

In a real world, the mixed-crop-livestock production occurs within a more complex tree-crop-livestock system known as agroforestry system (AFS) that characterizes most West African agro-systems. An agroforestry system is an intentional or purposeful integrating and managing trees and woody shrubs with crop and/or livestock farming (Nair, 2005). Such a system may help to reduce anthropogenic pressure on forest resources and thus contribute to integrated strategies of natural resource management and forest conservation (Kumar and Nair, 2011). The system can store aboveground carbon in a range of 0.29 to 15.21 Mg C/ha/year, and soil carbon in a range of 30-300 Mg C/ha up to 1 m depth in the soil (Nair et al., 2010). Beyond carbon storage and biodiversity conservation, other benefits of AFS are soil fertility and increased food production.

Little information exists on the aspect of crop-livestock integration as part of a much larger system (AFS) and its role in the system's maintenance or functioning. Studies usually focus more on the role of trees and crop management in the AFS, but very few focused on the livestock component. Across SSA and West Africa, the livestock module is an integral part of AFS. The current study, therefore, attempts a more holistic analysis of CLI as a resilient strategy to climate change.

Besides greenhouse gas emission and mitigation, another important aspect within the global tree-crop-livestock system is crop and livestock water productivity in the face of climate change. Most of the climatic impacts are expected to result from changes in the water cycle. Therefore, rainfall variability and the subsequent increase in the frequency of extreme weather events, combined with an accelerated water cycle (through high evapotranspiration), will affect each element in agricultural ecosystems: crops, livestock, trees, fish, and rural communities (Palombi and Sessa, 2013). For this reason, climate change adaptation strategies for agriculture will need to be viewed through a 'water lens' (Palombi and Sessa, 2013).

Such strategies could consist of a set of agricultural practices aiming at increasing agricultural soil water holding capacities, maintaining and replenishing soil fertility, and valuing crop and livestock water productivity within the mixed farming systems.

Improving water productivity means producing more per drop of water and this is of great interest to areas with recurrent drought, such as the SSA countries characterized by arid and semi-arid areas, where climate change is adding more burdens on already stretched water resources (Palombi and Sessa, 2013).

In Burkina Faso, studies have been conducted on farming systems water productivity (Amole et al., 2021), still few were related to the interactions between crop-livestock integration and water productivity within the Sudan, Sudan-Sahel, and Sahel agroclimatic zones.

Another challenge directly related to the system productivity is that soils in West Africa are structurally degraded with low nutrient content (Soler et al., 2011).

However, soil organic matter (SOM) plays a central role in soil fertility maintenance through stabilizing soil structure and cycling of organically held plant nutrients (Soler et al., 2011). In this regard, sequestration and turnover of the SOM have been at the centre of scientific debates for decades (Lal, 2007; Lal et al., 2007; Oades and Waters, 1991; Tiessen et al., 1994). Within West African agro-systems, soil fertility improvement and the increase of land productivity can rely on the use of nitrogen-fixing crops (peanut or cowpea) in rotation (Bado, 2002; Bado et al., 2006b), and the effective combination of chemical and animal manure (Bado et al., 2006a; Soler et al., 2011). Crop-livestock integration offers an additional option for fertility maintenance. Beyond fertility control in the system, soil carbon plays an important role in farm-scale greenhouse gas balance (through sequestration and release) and likewise affects atmospheric carbon dioxide ($CO_2$) levels (Soler et al., 2011; Tiessen et al., 1998). From the above description of the mixed farming characteristics of West African agro-systems, a better understanding of the complex interactions and processes occurring between the system components is needed. This could be on the interactions between crop-livestock integration and GHGs emissions (from practices), mitigation (through tree and soil sequestration), soils properties and water use efficiency. That could give insights on improving productivity within mixed farming systems and mitigating climate change across climatic zones for more resilient farmers and farming systems. The current research aims to investigate CLI's influence on greenhouse gas emissions, tree diversity and carbon storage, crop and animal water productivity and soil properties, and carbon storage.

It is expected that the findings give information on the needed actions to take to mitigate climate change and enhance water productivity for small farmers' benefit.

This, ultimately, is intended to build resilience in a water stressed region such as Burkina Faso.

## 6.2 Study Methods

### 6.2.1 Study area

The study area consisted of three study sites, hereby referred to as districts selected across the three climatic zones of Burkina Faso (Figure 6.1). These districts were Dori (between latitudes 13°45'36"N / 14°19'12"N and longitudes 0°24'0" W /0°16'12" E), in the Sahel zone, Niou (between latitudes 12°40'12"N / 12°54'36"N and longitudes 1°58'48"W /1°41'24"W) in the Sudan-sahel zone and Dano (between latitudes 10°58'48"N / 11°12'36"N and longitudes 3°6'36"W /2°57'0"W) in the Sudan zone. The study districts are all aligned along a climatic gradient characterised by an increasing mean annual precipitation (300-600 mm to 900-1,200 mm) and decreasing mean annual temperature (25-35°C to 20-25°C) as one moves from the Sahel to the Sudan zone. If agro-pastoral activities are the main occupation of farmers in the studied zones, some differences are observed with regards to livestock and crop farming when moving from the North to the South. In all cases, farmers exploit environmental opportunities in choosing activities that adequately support their livelihoods.

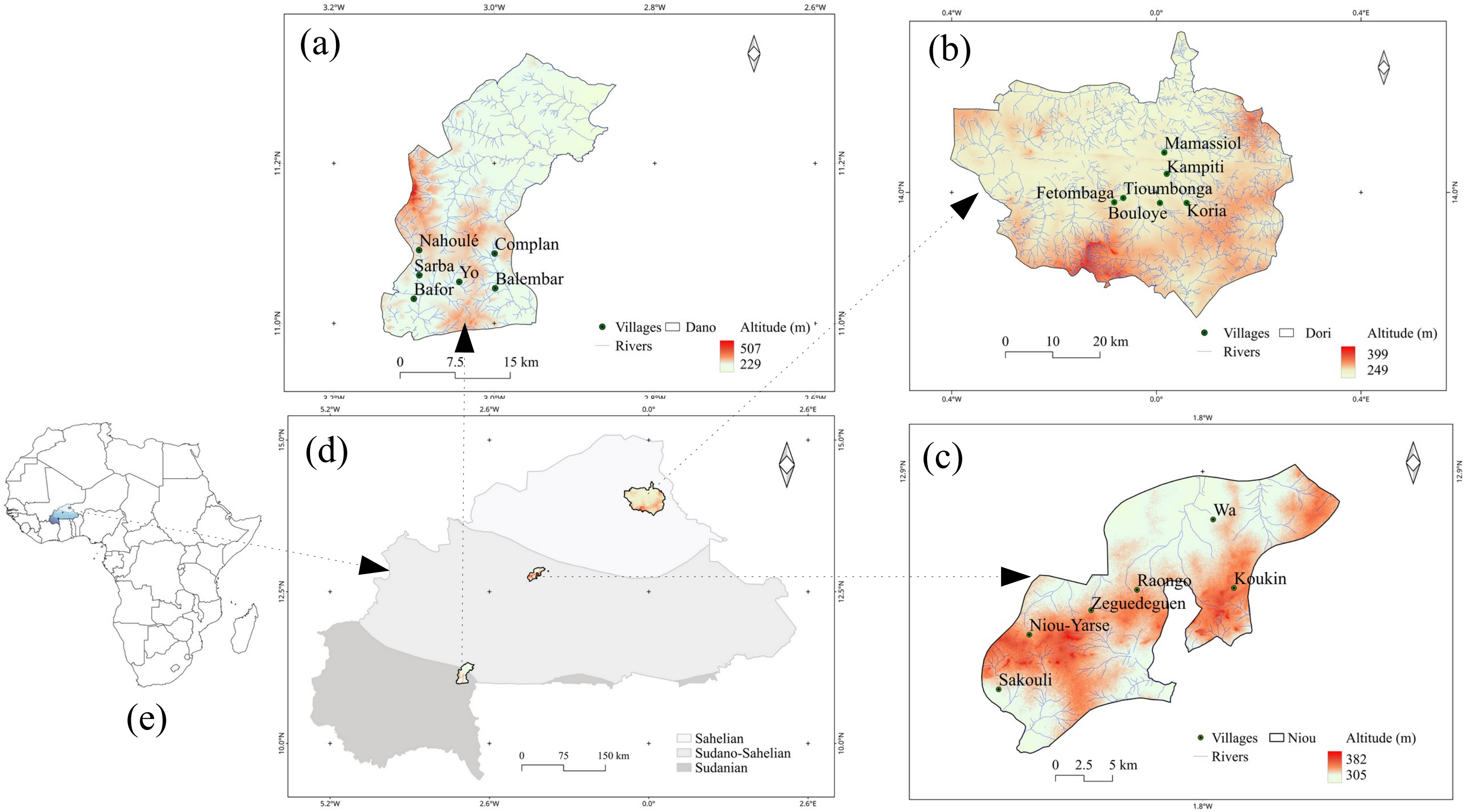


Figure 6.1: Location of the study districts across climatic zones of Burkina Faso. (a) Dano district in the Sudan zone; (b) Dori district in the Sahel zone; (c) Niou district in the Sudan-Sahel zon; (d) and (e) Map of Burkina Faso and Africa respectively (Source: Sanou, 2023).

### 6.2.2 Data collection

The study of crop-livestock water productivity, greenhouse gases estimation, carbon sequestration and soil properties demands a set of data and data sources as shown in Table 6.1. The sampling method used for data collection was the same as described in the chapter 5.

Table 6.1: Data collection

| Designation | Type of data | Sources |
|---|---|---|
| Greenhouse gases emission | Livestock ownership<br>Land holding<br>Crop type<br>Cropped area (ha)<br>Emission factors | Primary data from survey and secondary data (Appendix 6) |
| Water-productivity | Livestock ownership<br>Land holding<br>Cropped area (ha)<br>Grazing area (ha)<br>Feed sources (crop residues, pastures)<br>Crop and livestock outputs<br>Crop coefficients | |
| Carbon sequestration and soils properties | Tree species, diameter and height<br>Top-soils sample 0-20 cm | Primary data from field measurement and laboratory analysis |

Source: Author's Own compilation, 2023.

#### 6.2.2.1 Greenhouse gases emission

The following sources were considered: (i) $CH_4$ emissions from enteric fermentation; (ii) $N_2O$ and $CH_4$ emissions from animal manure management; (iii) $CO_2$, and $N_2O$ emissions related to the use of synthetic fertilizer (Urea, NPK); (iv) direct $N_2O$ emissions from dung inputs to grazed soils.

Due to insufficient information on some factors needed for emissions estimation, the following sources were not considered in this study: (i) $CH_4$ emission from rice cultivation; (ii) $CO_2$ emissions from liming; (iii) $CO_2$ emissions from livestock respiration; (iv) indirect $N_2O$ emissions from manure management; (v) direct $N_2O$ emissions produced from managed organic soils; (vi) emissions from other agricultural inputs, such as pesticides and seeds (These were considered negligible and therefore not included in the analysis) (Kramer et al., 1999); (vii) emission from the production of investment goods (machines and buildings) and those related to consumption of fossil fuels (both for on-farm and off-farm activities). Furthermore, it was assumed that soil organic carbon stocks remained unchanged, therefore indirect $N_2O$ emissions induced by leaching of $NO_3^-$ or $NH_3$ volatilization from managed soils were not considered (Flessa et al., 2002).

The emission factors were derived from data on greenhouse gas emissions described in the literature (IPCC, 2006; Samsonstuen et al., 2019). All the emissions estimated from each farming system were converted to $CO_2$ equivalents using the global warming potential (GWP), which determines the relative contribution of gas to the greenhouse effect. The GWP index represents the cumulative radiative forces between the present and a selected time in the future caused by a unit mass of a particular gas emitted now (IPCC, 1996). The GWP (with a period of 20 years) of $CO_2$, $CH_4$ and $N_2O$ are 1, 56 and 280, respectively. The emissions of $CO_2$, $N_2O$, $CH_4$ and $CO_2$ equivalents were determined from the respective sources in each farming system (Flessa et al., 2002).

The Tier 1 approach was used for emission calculation and consisted of using emission factors provided by (IPCC, 2006) for each livestock species, manure management systems, fertilizer inputs (Appendix 7). The Tier 1 method will likely be suitable if enhanced characterisation data are unavailable (IPCC, 2006).

#### 6.2.2.2 Tree diversity and carbon sequestration

***Sampling design and farmland tree inventory***

Farmlands were selected from farms belonging to 589 farmers across the three climatic zones. These farmers were involved in tree-crop-livestock systems. To take account of climate gradient, sixty (60) farmers were randomly selected in each climatic zone: Dori in the Sahel, Niou in the Sudan-Sahel and Dano in the Sudan zone. Thus a total of one-hundred and eighty (180) farmlands were involved with each farm located at least 500 meters from the next farm. In each zone, agricultural landscape could involve house fields, village fields, bush fields (Bayala et al., 2011), and each field category being particularly characterised by a given type of pressure from or interrelation with communities based on the distance between them. To avoid bias in the study, farmlands were selected to be far from the homestead (bush fields) to avoid the influence of people's proximity. Bayala et al. (2011) indicated an increasing species richness from house fields to bush fields due to higher pressure exerted on this farmed land-use type due to its proximity with human settlements. The bush fields have less pressure and are more frequently left to fallow. Tree inventories were conducted in the selected farmlands from March to June 2021 using a systematic sampling scheme. For higher precision in carbon storage potential within agroforestry land uses, a systematic inventory method of tree species was conducted within cropped areas (Neya et al., 2018a). The size of inventoried farmlands areas varied between 2,500 $m^2$ and 30,000 $m^2$ to account for the minimal area of 2,500 $m^2$ (Thiombiano et al., 2016) recommended for tree inventories in agroforestry systems. The farm area was estimated by delineating with the tracking function of the Global Positioning System (GPS). In each farmland, shrubs and trees with a diameter at breast height higher than 5 cm were inventoried. We collected species names and measured stem diameter at breast height (DBH) and total tree height. Overall, 4733 individual trees were measured within a total area of 243.2 ha across the three climatic zones.

***Species diversity, stand structure and carbon stock***

Three most important indices commonly used to assess species diversity were used. These diversity indices were species richness (S), Shannon's index (H) and Simpson's index (D). The R package 'BiodiversityR' (Kindt and Coe, 2005) was used to compute the three diversity indices. To compute the diversity indices, the dendrometry data were first transformed into an abundance/dominance matrix following Braun-blanquet (1932).

Non-destructive method was applied to convert field measurements into aboveground biomass (AGB). This was done using a local mixed allometric model (Equation 6.1) developed for biomass estimates in West African savanna ecosystems (Ganamé et al., 2021). A second equation was used to compute the below-ground biomass (Cairns et al., 1997; Somarriba et al., 2013; Tiga, 2019)(Equation 6.2). The allometric models combine stem diameter at breast height, tree height and wood density as follows:

$$AGB = 0.0673\left(\rho\, DBH^2\, H\right)^{0.976} \quad \text{equation 6.1}$$

$$BGB = \exp\left(-1.0587 + 0.8836\ln\left(AGB\right)\right) \quad \text{equation 6.2}$$

Where *AGB* is aboveground biomass (kg/tree), *DBH* is the diameter at breast height (cm), *H* is the tree total height (m) and ρ is wood-specific density (g/cm$^3$).

The mean values of wood density (*ρ*) were extracted from the global wood density database (Zanne et al., 2009) using the R package 'BIOMASS' (Réjou-Méchain et al., 2017). The value was assigned at the species or genus level. Biomass was computed for each tree, summed up for each farm, and afterward scaled to hectare using the size of the farmland. The value of *AGB* per hectare (Mg/ha) was finally converted into carbon stock (Mg C/ha) using the standard conversion factor of 50 % (Penman et al., 2003).

Finally, the equivalent total carbon dioxide ($CO_2$) removal from the biomass was computed using the following equation:

$$CO_2 - Biomass = TB(0.5)\left(\frac{44}{12}\right) \quad \text{equation 6.3}$$

Where *$CO_2$-Biomass* is the total carbon dioxide sequestrated (Mg/ha), *TB* is the total biomass quantified (kg/tree); *44* and *12* represent the weight (g) of one molecule of $CO_2$ and carbon respectively.

#### 6.2.2.3 Crop-livestock water productivity

Water productivity is a function of depleted water and the beneficial outputs from crops and livestock (Peden et al., 2007a). Indeed, crop water productivity (CWP) is the a ratio of crop yield (physical productivity) or its financial value (financial productivity) to the amount of water depleted to produce crop grain (Haileslassie et al., 2009a, 2009b). Similarly, Livestock Water Productivity (LWP) is the ratio of net livestock-related benefits, including both products and services, to the water depleted and degraded in producing these (Gebreselassie et al., 2009; Haileslassie et al., 2009a, 2009b).

CWP and LWP were computed using equation 6.4 and 6.5:

$$CWP = \frac{C_j P_j}{(ET_o K_{cj} \beta_j)} \qquad \text{equation 6.4}$$

where *CWP* is crop water productivity of crop type *j* at household level; $C_j$ is the yield of crop type j (kg); $P_j$ is market value of crop *j* (US$/kg); $\beta_j$ ($m^2$) is land area under crop *j*; $ET_o$ (mm) is the reference evapotranspiration; $K_cj$ is coefficient of crop type *j* obtained from FAO database (Smith, 2000). In the equation 6.4, $K_c$ consisted of the mean value of different growth stage crop coefficient (FAO, 1998). $K_c$ value, here already considered the length of the growing period.

$$LWP_i = \frac{\sum_{i-1}^{n} (O_i P_i + S_i P_i)}{\sum_{k-1}^{n} WD_k} \qquad \text{equation 6.5}$$

where *i* is the unit of observation per household, LWP is livestock water productivity (US$/$m^3$), $O_i$ the quantity of livestock outputs (milk, flock offtake, and manure), $S_i$ the service type (traction, ploughing) obtained per year, $P_i$ the local market price (US$) of each output and service type; $WD_k$ the amount of water depleted in evapotranspiration for production of animal feed resources (crop residues ($WD_{CR}$), grazing land ($WD_{GL}$)).

***Depleted water estimation***

The estimation of the depleted water in crop and livestock production was a function of water lost through evapotranspiration (*ET*) during production processes. The computation of $ET$ used crop coefficient ($K_c$) for different stages of development for each crop type using equation 6.6 (Amole et al., 2021).

The $K_c$ for different crop types cultivated was determined from the literature (FAO, 1998). The $K_c$ values for grazing land were estimated after Diouf et al. (2016) which gave an indication of the mean crop coefficient ($K_c$) for Sahel rangelands. Besides crop coefficients, the growing period or stage of each crop type (FAO, 1998) and rangeland (Diouf et al., 2016) were also determined. Information of the growing periods found in the literature was cross-checked by the state extension services in charge of agriculture in the study zones.

$$ET_{ci} = \sum_{t=0}^{T} \left( ET_o K_{ci} LGP_i \right) \qquad \text{equation 6.6}$$

where $ET_{ci}$ is the total water depleted for crop $i$ biomass (grain and crop residues) or grazing land in meters per hectare during the growing season; $ET_o$ is the average reference evapotranspiration (mm/d); $K_{ci}$ is crop coefficient of the crop type/grazing land $i$ at different growth stages $t$; $LGP_i$ is the length of the growing period in days of the crop types/grazing land.

The Reference Evapotranspiration ($ET_o$) values were computed for each climatic zone using the Penman-Monteith method as a standard method of computation (FAO, 1998). The data needed include temperature, relative humidity, wind speed, and solar radiation (Mekonnen et al., 2011).

Water depleted for crop grain *($WD_C$)* production is estimated using equation 6.7 (Haileslassie et al., 2009b).

$$WD_{cj} = \sum_{i} \left( ET_{cij} HI_{ij} \beta_{ij} \right) \qquad \text{equation 6.7}$$

where $WD_{ci}$ is the total water depleted for crop $i$ grain production; $ET_{cij}$ is Evapotranspiration for crop $i$ in household $j$ (mm); $\beta_{ij}$ is the Growing area of crop $i$ types in household $j$ ($m^2$); $HI_{ij}$ is the harvest index of crop $i$ in household $j$.

The water depleted for crop residues ($WD_{CR}$) production is estimated using equation 6.8:

$$WD_{CRj} = \sum_i \left( ET_{cij} \left(1 - HI_{ij}\right) CR_{ij} \beta_{ij} \right) \qquad \text{equation 6.8}$$

Where $WD_{CRj}$ is Water depleted for crop $i$ residues in household $j$ (mm); $ET_{cij}$ is Evapotranspiration for crop $i$ in household $j$ (mm); $\beta_{ij}$ is Growing area of crop i types in household $j$ ($m^2$); $CR_{ij}$ is Utilization factor of the crop residue of crop $i$ for household $j$ (fraction).

Water Depleted for communal grazing lands is estimated using the equation 6.9.

$$WD_{GLj} = ET_{c,gr} GL_j FU_{GL} 10 \qquad \text{equation 6.9}$$

Where, $WD_{GL}$ is total water depleted for biomass production on grazing lands for household $j$ ($m^3$); $ET_{c,gr}$ is evapotranspiration for biomass production on grazing land (mm); $GL_j$ is grazing land area available for household $j$ (ha); $FU_{GL}$ is feed use factor for the grazing land (fraction).

Assumptions and Secondary Data Sourcing

A number of assumptions were made in the process of water productivity estimation: (i) The depleted water (*ET*) for purchased feeds was not considered in the current study, as suggested by (Houenou et al., 2012). Indeed, as indicated by Amole et al. (2021), there is not enough credible information on the quantity, type, and frequency of purchase of feeds. (ii) The factor of tropical livestock unit per hectare (TLU/ha) was used to allocate the share of each household's livestock owner from the communal grazing areas (Haileslassie et al., 2009b). This was done assuming equal access to feed available from communal grazing areas per household (Amole et al., 2021). A total livestock density of 0.2 TLU/ha was the average livestock density for Sahel and Sudan-Sahel zones, while 0.4 TLU/ha was the average density for the Sudan zone (Ouédraogo, 2011). (iii) Grazing land feed use-factor of 45 % was assumed as an average of the value of available dry matter (DM) accessible to livestock during the wet and dry season for grazing lands in similar agro-ecological conditions (Amole et al., 2021).

***Estimation of crop beneficial outputs***

Information on 2020/2021 average yields (kg/ha/y) for the major crops cultivated in each studied zone were obtained from farming household heads. The crop types were maize, millet, sorghum, groundnut, cowpea and sesame. The market values of each crop were estimated based on the current local market price of each crop (USD/kg).

***Estimation of livestock beneficial outputs***

Livestock beneficial outputs were products (milk, meat, manure) and services (traction, and transportation). All the estimations of livestock output were done on a yearly basis, especially for the campaign 2020-2021.

The following approach was adopted in the estimation of livestock beneficial outputs:

(i) Manure production and its fertilizer values: Livestock holdings were converted to the equivalent Tropical Livestock Unit (TLU) using a conversion factor of 0.70 TLU/head for cattle and donkey and 0.10 TLU/head for sheep and goats (FAO, 2003). Dry weight daily dung production of 1.03, 1.76 and 1.85 kg/d/TLU were used for cattle, sheep and goat respectively (Bidjokazo et al., 2011a). The total annual dung produced was, therefore, estimated for the different farming systems.

Livestock's dung nutrient contents (N, P, K) were estimated based on the average chemical composition of cattle manure (9.0-20 g N/kg, 4.0-10.0 g P/kg and 22.0-56.0 g K/kg) (Bidjokazo et al., 2011b; Gomgnimbou et al., 2014) and sheep and goat manure (14.0 g N/kg, 4.0 g P/kg and 54.0 g K/kg) in Burkina Faso (Bidjokazo et al., 2011b). To determine these nutrient values, each nutrient (N, P, K) quantity was converted to fertilizer equivalent monetary value using the current local market price of chemical fertilizer (i.e the price of 50 kg bag of NPK). The local market prices, including handling and transportation costs of 50 kg/bag of $N_{14}P_{23}$ $K_{14}$ fertilizers (14 % N, 23 % P and 14 % K) were 32.0 USD, 32.9 USD and 38.0 USD in the Sudan-Sahel (Niou), Sudan (Dano) and Sahel (Dori) respectively. The beneficial value of urine was not considered in this research due to the lack of reliable data on the volume of production and nutrient concentration.

(ii) Milk production: yearly annual milk production was estimated as a function of the number of lactating cows, lactation period and daily milk production (l/d/cow) in the study area. The monetary value of the estimated milk quantity was determined based on the current local market price of fresh milk (USD/l) in the study area.

(iii) Offtake rate and meat value: the estimation was done based on off-take rate assuming carcass weight of 52 % for bovines and 46 % for 'shoats' (sheep and goats) (FAO, 1999) and the age of maturity were taken as 5 years, 5.5 years and 1.5 years for cattle, donkey and goat/sheep respectively (Houenou et al., 2012). To avoid an overestimation of livestock water productivity (given that a yearly water depleted to produce feed cannot solely account for the carcass weight) and ensure that the productivity computed reflected that of the considered period (2020-2021), the monetary value of the meat produced by each livestock was divided by its maturity age (Houenou et al., 2012). This allowed for estimating the annual meat and other livestock output values in the calculation of LWP as a ratio of yearly output to the yearly water depleted.

In this study, the values of hides and skins were not considered because the assumption made considered only the potential offtake of livestock (no slaughter) from the farmers' households (Amole et al., 2021).

(iv) Value of livestock services: within the three study zones, animal draft power constitutes a key beneficial output to farm households. The livestock service also includes the transportation of crop residues from farms to homesteads and organic fertilizers (compost, dung, household waste etc.) from homesteads to cropped fields. The evaluation of these livestock services was done by multiplying the daily hiring cost (USD/d) of draft animals (oxen and equines) by their respective number of working days per year spent in transportation or cropping (ploughing, weeding) for each household (Otte and Chilonda, 2002).

#### 6.2.2.4 Soil properties and carbon sequestration

***Soil sampling method***

Soil samples were collected across two of the three climatic zones (Sudan and Sudan-Sahel). Due to the insecurity issue, Dori in the Sahel zone was not accessible. Therefore, data collection could not be completed in the zone. Soil core sampler (5cm diameter×5cm length) was used to collect samples at two (2) points on the diagonal (from the two corners) (Figure 6.2) of each plot (50m x 50m) at a depth of 0 - 20 cm for bulk density determination (IPCC, 2007c).

Additional samples were taken at five locations (from the four corners and one from the middle) (Figure 6.2) on each plot, also at a depth of 0 – 20 cm. The obtained samples were thoroughly mixed to get composite samples for the determination of SOC concentrations from the laboratory. In total, 120 composite soil samples (Sudan zone: 60 samples; Sudan-Sahel zone: 60 samples) were collected for the determination of soil chemical properties (pH, % C, N, P, K) and 240 other samples for soil bulk density determination.

SOC was computed as a function of the bulk density and the percentage of carbon provided from the laboratory analysis using equation 6.10 (Pluske et al., 2014) and equation 6.11.

$$SOC = 100 \rho Z C \qquad \text{equation 6.10}$$

$$\rho = \frac{Ms}{Vs} \qquad \text{equation 6.11}$$

Where *SOC* is the soil organic carbon stocks (Mg/ha); $\rho$ is the soil bulk density (Mg/$m^3$); *Z* is the soil depth (m); *C* is the carbon concentration (%); *Ms* is the mass of the soil (g), and *Vs* is the volume of the soil ($cm^3$) [1 g/$cm^3$ = 1Mg/$m^3$].

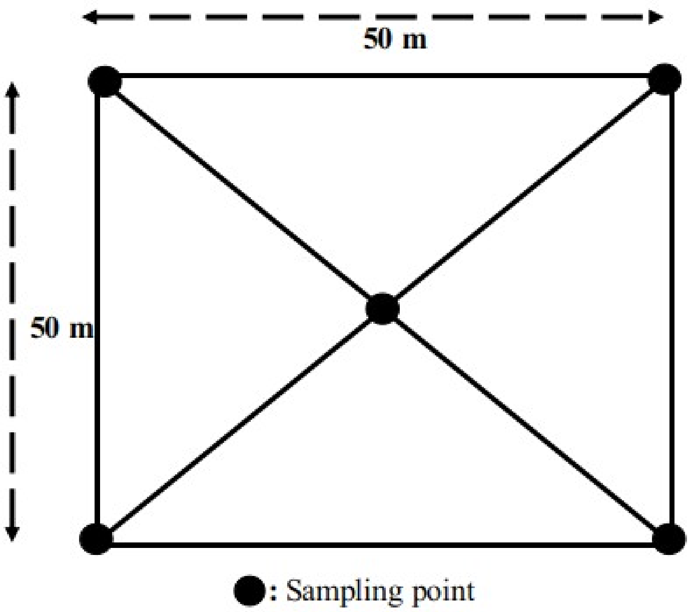


Figure 6.2: Representation of the sampling points on each plot. Source: Author's Own construction, 2023.

The equivalent total carbon dioxide ($CO_2$) sequestrated by agricultural land was computed using the following equation:

$$CO_2 - Soil = SOC\left(\frac{44}{12}\right) \qquad \text{equation 6.12}$$

Where $CO_2$*-Soil* is the total carbon dioxide sequestrated (Mg/ha), *SOC* is the total Soil total carbon (Mg/ha/household); 44 and 12 represent the weight (g) of one molecule of $CO_2$ and carbon respectively.

***Laboratory analysis***

Soil samples were sent to *'Bureau National des Sols (BUNASOLS) du Burkina Faso'* for analysis of chemical parameters (pH, total nitrogen (N), assimilable phosphorus (P), and potassium (K)), according to the methods of Tran and Boko (1978). Bulk density was determined using the oven method, where samples were dried at 105°C until a constant weight was achieved. The dry weight was divided by sample volumes to obtain the bulk density. The Walkley-Black wet oxidation method was used for organic carbon concentration determination.

The soil-water ratio method was used for pH determination; total nitrogen was determined by the Kjeldahl method (Hillebrand et al., 1953); the assimilable phosphorus by the Bray method (Bray and Kurtz, 1945); and the method of Walinga et al. (1989) was used for the determination soil potassium.

***Soil fertility assessment***

Soil fertility status assessment was based on the analysis and interpretation of data such as total Nitrogen content ($N_T$), $pH_{water}$, Potassium (K), Phosphorus (P), and Soil Organic Carbon (SOC). Soil fertility levels were determined by the method of maximum limitations according to the criteria defined in Table 6.2 (Dabin, 1956; Sys et al., 1993). In this perspective, the pH, N, P, K and soil organic carbon percentage within Sudan and Sudan-Sahel were checked against their required levels for suitable land fertility. The following classes of fertility were set:

**Class 0, optimal fertility level:** no limitation the soil characteristic is optimal.

**Class I, high fertility level:** soils are in this class when the characteristics have no or only four slight limitations. This class refers to situations that could slightly reduce yields without requiring special cultivation techniques.

**Class II, medium fertility level:** soils are in this class when the characteristics do not present more than three moderate limitations, possibly combined with low limitations. This class refers to situations that cause a greater decrease in yields or the use of special cultivation techniques.

**Class III, low fertility level:** soils are in this class when their characteristics show more than three moderate limitations associated with one severe limitation. This class refers to situations that cause a decrease in yields or the implementation of cultivation techniques that could jeopardise profitability.

**Class IV, very low fertility level:** soils are in this class when their characteristics present more than one severe limitation.

Table 6.2: Evaluation criteria for soil fertility classes

| Characteristics | Level of fertility | | | | |
|---|---|---|---|---|---|
| | Very high (no limitations) | High (low limitation) | Average (moderate limitations) | Low (severe limitations) | Very low (very severe limitations) |
| | Degree 0 | Degree I | Degree II | Degree III | Degree IV |
| N (%) | > 0.08 | 0.08-0.06 | 0.06-0.045 | 0.045-0.03 | < 0.03 |
| Potassium (K) ($cmol^{+}/kg$) | > 0.4 | 0.4 - 0.3 | 0.3 - 0.2 | 0.2 - 0.1 | < 0.1 |
| $P_{ass}$ ($cmol^{+}/kg$) | > 20 | 20 - 15 | 15 - 10 | 10 - 5 | < 5 |
| SOC (%) | > 2 | 2.0 - 1.2 | 1.2 - 0.8 | < 0.8 | - |
| pH | 5.5 - 6.5 | 5.5 - 6.0 | 5.5 - 5.3 | 5.3 - 5.2 | < 5.2 |
| | 6.5 - 7.2 | 7.2 - 7.8 | 7.8 - 8.3 | 8.3 - 8.5 | > 8.5 |

(Source: Dabin, 1956; Sys et al., 1993)

Except for soil carbon and properties analysis that used t-test for comparing the two zones (Sudan-Sahel and Sudan), statistical analysis followed the same methodology adopted in Chapter 5.

### 6.2.3 Influence of crop-livestock integration on water productivity, emission and carbon sequestration

The relationship between integration indicators and water productivity (CWP, LWP), greenhouse gas emission, carbon sequestration and soil properties was checked using a Pearson correlation analysis. Furthermore, soil nutrient contents ($N_{soil}$, $P_{soil}$, $K_{soil}$) were checked against organic manure nutrient contents ($N_{dung}$, $P_{dung}$, $K_{dung}$) and chemical fertilizer nutrient contents ($N_{ch}$, $P_{ch}$, $K_{ch}$). This made it possible to explain at this stage of crop-livestock integration whether it was manure or rather chemical fertilizers that controlled soil fertility the most.

#### 6.2.3.1 Best combination of crop-livestock integration for sustainability

The essence of the study was to investigate which combination of livestock and cropping module could better ensure farmers' resilience and the sustainability of the integrated system in Burkina Faso. The determination of this best combination of crop-livestock components was therefore, based on the level of greenhouse gas emission (GHG), carbon sequestration and water productivity of the integrated system. To this end, a Principal Component Analysis was performed on variables (integration effectiveness, water productivity, carbon sequestration and greenhouse gases emissions) where individuals consisted of 180 farming households. The PCA allowed dataset dimensions reduction into non-correlated dimensions that explains much of the variance of the original dataset. Subsequently, Hierarchical Ascendant Clustering was performed in R-software, on the 180 farming households. Data used were on-farm carbon sequestration potential, farm productivity and associated emissions to derive a cluster of households based on their level of production and the ecological performance of their production system. Ward's method, and the gap statistic (Tibshirani et al., 2001) were used to perform hierarchical clustering and to infer the appropriate number of clusters respectively. The cluster that combines at the same time both good production and ecological performance constitutes the class of better crop-livestock combination.

## 6.3 Results and Discussion

### 6.3.1 Greenhouse gases emission

#### 6.3.1.1 Sources and types of greenhouse gases emission

Generally, the highest amount of greenhouse gas (GHGs) ($CO_2$, $CH_4$, $N_2O$) emission was experienced in the Sudan zone ($p < 0.05$). Carbon dioxide ($CO_2$) (basically from chemical ferilizer in this study), amounted 33.07±28.29 and 11.84±9.64 kg/household/y in the Sudan and Sudan-Sahel zones, respectively. The quantity of methane ($CH_4$) emitted per household in the year decreased from 209.46 ± 207.42 kg through 126.65±104.19 kg to 124.34±113.16 kg within Sudan, Sudan-Sahel and Sahel zones, respectively. Nitrous dioxide emission ($N_2O$) showed a similar decreasing trend, with the highest amount in the Sudan zone (1.89±1.83 kg/household/y), followed by the Sudan-Sahel zone (0.57±0.54kg/household/y) and the Sahel zone (0.14±0.14 kg/household/y) (Table 6.3). This situation is explained by the fact that in the Sudan zone, the sedentary extensive large farmers have bigger herd sizes and cropped areas with the highest use of chemical fertilizers (urea, NPK). The more the cattle, the more the emission of methane both from enteric fermentation and manure management. Similarly, the nitrous oxide emission in the farming system depends highly on livestock manure amount and management. Furthermore, the more the use of chemical fertilizer (NPK, Urea), the more the emission of $CO_2$ and $N_2O$. Indeed, the main sources and types of greenhouse gases from livestock systems are $CH_4$ from enteric fermentation and manure management,

$CO_2$ from land use and its changes and $N_2O$ from manure management (Zervas and Tsiplakou, 2012). Overall, the findings align with the thesis that enteric fermentation is the largest source of emissions from agriculture in the continent, accounting for more than half of the total agricultural emissions (Tongwane and Moeletsi, 2018).

Emission estimation from agricultural activities presents uncertainties (Boateng et al., 2017; Kim et al., 2016; Tongwane and Moeletsi, 2018; Zhu et al., 2016), due to several factors, including the lack of tropical zone-specific emission factors from different herd species. Research studies makes use of emission factors calibrated with respect to temperate conditions which do not suit tropical conditions (Boateng et al., 2017). This could be one limitation of the current study.

Table 6.3: Greenhouse gas emission across climatic zones (kg /household/y)

| Districts | $CO_2$ | $CH_4$ | $N_2O$ |
|---|---|---|---|
| Dano | $33.07 \pm 28.29^a$ | $209.46 \pm 207.42^a$ | $1.89 \pm 1.83^a$ |
| Niou | $11.84 \pm 9.64^b$ | $126.65 \pm 104.19^b$ | $0.57 \pm 0.54^c$ |
| Dori | - | $124.34 \pm 113.16^b$ | $0.14 \pm 0.14^b$ |

Source: Author's Own computation, 2023.

#### 6.3.1.2 Contribution of each greenhouse to the total emission

Among greenhouse gases (GHGs) emitted, methane from enteric fermentation (enteric $CH_4$) is the major contributor to total emissions (carbon dioxide equivalent) (Figure 6.3) ($p < 0.05$). Previous literature similarly indicated that enteric fermentation emits more carbon dioxide equivalent ($CO_2e$) from methane (Tongwane and Moeletsi, 2021) than manure emits as methane and nitrous oxide together (Gaitán et al., 2016). This situation is highly dependent on the animal's nutritional and energy efficiency; that also depends on the quality of feed grazed (digestibility and protein content) (Gaitán et al., 2016). Indeed, these authors indicated that livestock that fed on poor quality feed emitted more methane. In contrast, an improved livestock diet resulted in lower values of methane and nitrous oxide emissions. Thus improving fodder quality and adopting better feeding strategies are ways of mitigating greenhouse gas emissions. This improvement has to do with a better storage condition of crop residues to avoid quality decline. Common practices across zones are storing crop residues and other fodder types on the top of houses, trees and shelters. Plate 6.1 shows storage conditions of fodder for dry season (February-June) in the Sudan-Sahel zone (A) and Sahel Zone (B).


Plate 6.1: Storage conditions of fodder for dry season grazing (February-June) within the Sudan-Sahel zone (A) and Sahel Zone (B). Source: author's Own compilation, 2023.

The stored fodder is also exposed to weather (rainfall, heat stress) that causes nutritional quality to decline. After the enteric fermentation (87.3-95.2 % $CO_2$e) and manure methane (4.2-7.4 % $CO_2$e), emissions from nitrous oxide emission (0.8-6.1% $CO_2$e) were the third highest across zones. This was based on manure management (Plate 6.2) but more on using chemical fetilizer (Urea and NPK).

Plate 6.2: Example of poor management of manure on field in the Sahel zone. The best management could be a heap composting in a mixture with non grazed crop residues. Source: author's Own compilation, 2023.

Unlike Sudan and the Sudan-Sahel, the Sahel zone had the lowest emission of carbon dioxide equivalent from nitrous oxide. This is because the interviewed farmers' households did not use chemical fertilizers as used in the Sudan zone (373.7±361.7 kg/ha of NPK and 165.4 ± 141.5 kg/ha of Urea) and moderately applied in the Sudan-Sahel zone (104.8±78.8 kg/ha of NPK and 59.2 ± 48.2 kg/ha of Urea). Carbon dioxide emission was directly related to cropping activities, such as the use of urea that characterized the Sudan and Sudan-Sahel zones.

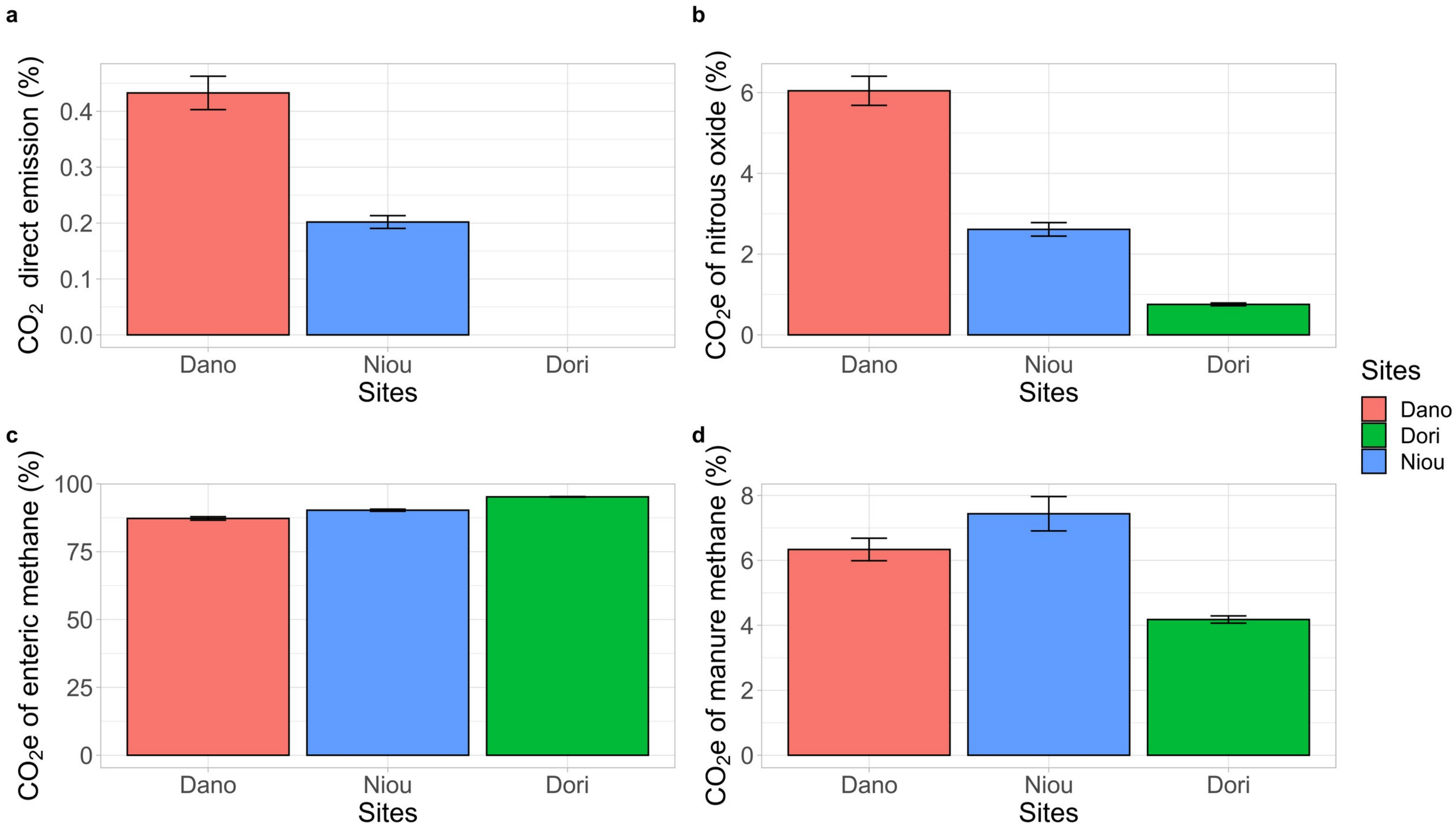


Figure 6.3: Contribution of each greenhouse gas type to the global emission in carbon dioxide equivalent (CO2e). (a) direct emission of carbon dioxide; (b) carbon dioxide equivalent from nitrous oxide emission; (c) carbon dioxide equivalent from enteric methane emission; (d) carbon dioxide equivalent from manure methane emission. Source: author's Own computation, 2023.

#### 6.3.1.3 Greenhouse global emission

The emissions decreased from the Sudan zone (12.9±12.8 Mg $CO_{2e}$ /y), through the Sudan-Sahel (7.3±5.9 Mg $CO_{2e}$ /y) to the Sahel zone (7.0±6.3 Mg $CO_{2e}$ /y). These results are beyond the range of 3.5- 4.4 Mg CO2e/year indicated by Ortiz-Gonzalo et al. (2017) in smallholder crop-livestock systems in Central Kenya. Similarly, the yearly amount of greenhouse gas emitted per tropical livestock unit (TLU) decreased from the Sudan (0.12±0.08 Mg $CO_{2e}$ /TLU/y) to similar figures for Sudan-Sahel (0.09±0.07 Mg $CO_{2e}$ /TLU/y) and the Sahel (0.09±0.05 Mg $CO_{2e}$ /TLU/y) zone. Also, the yearly emission of greenhouse gases per cropped area decreased from the Sudan zone (0.21±0.10 Mg $CO_{2e}$ /ha/y) to the Sudan-Sahel zone (0.09±0.07 Mg $CO_{2e}$ /ha/y) (Figure 6.4). In the Sudan zone, carbon dioxide equivalent emission per hectare is greater than the emission per TLU. It seems that the emission in this zone is more driven by cropping activities than livestock breeding. Inversely, in the Sudan-Sahel zone, the emission per hectare was similar to the emission per TLU. Finally, in the Sahel zone, the carbon dioxide equivalent emission for sedentary-extensive crop farmers seemed more driven by livestock breeding emission. This situation is explained by the comparatively low common use of chemical fertilizers (Urea, NPK) in the zone's rain-fed agriculture specialised in cereal cropping such as millet and sorghum (not very demanding regarding chemical fertilizers).

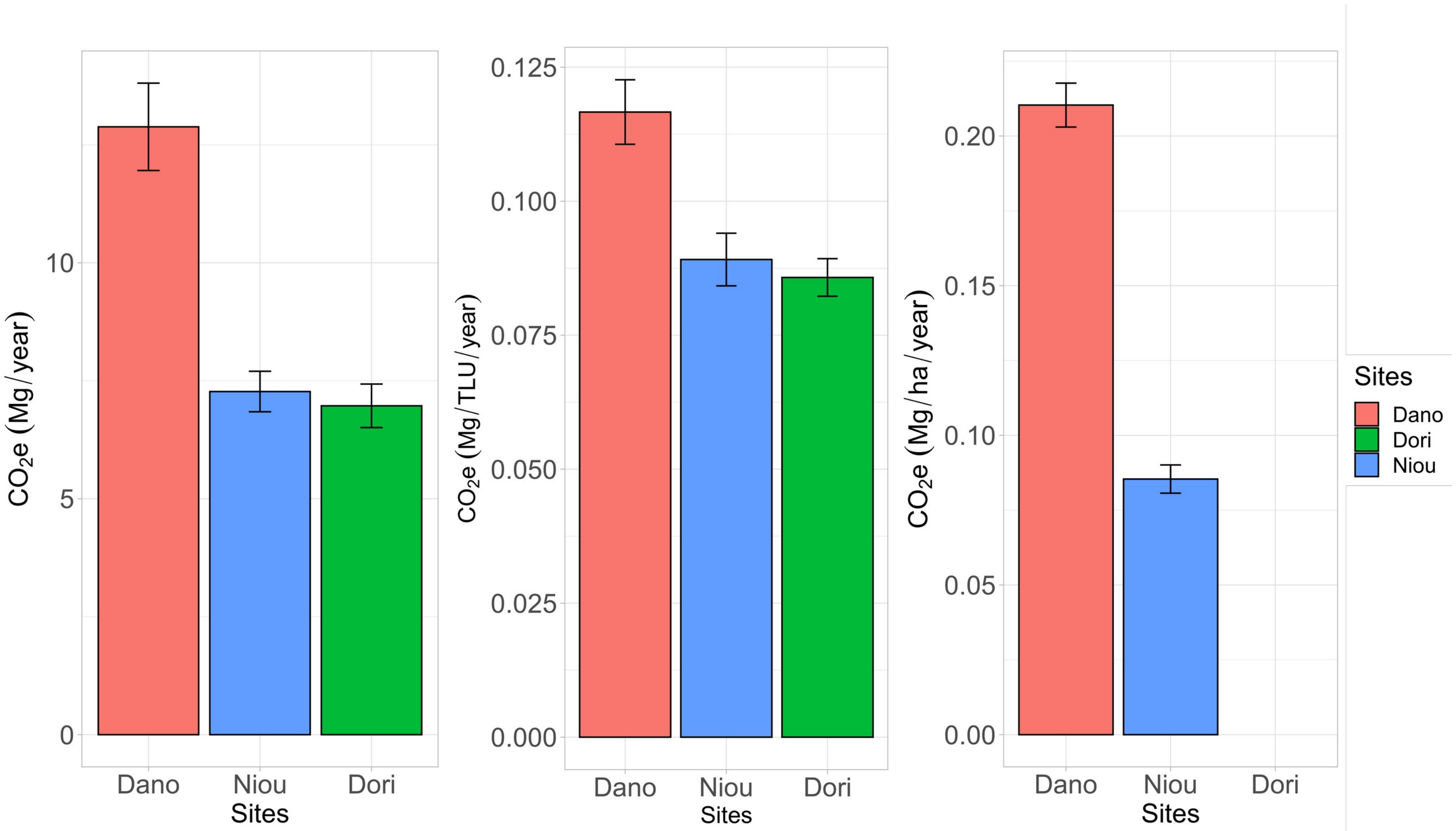


Figure 6.4: Yearly greenhouse gases emission. (a) global carbon dioxide equivalent emission; (b) carbon dioxide equivalent emission per hectare and (c) carbon dioxide equivalent emission per Tropical Livestock Unit. Source: author's Own computation, 20223.

The study also examined mitigation strategies. The following section reports findings of the sequestration potential of the mixed farming system across zones.

### 6.3.2 Tree diversity and carbon sequestration

Within the mixed-crop-livestock system in the study zones, trees play an important role in both carbon storage and biodiversity conservation. The study examined how tree diversity and carbon stock potential interrelate in the integrated crop-livestock system. The subsequent section of this chapter will address this question.

#### 6.3.2.1 Tree diversity within mixed crop-livestock system

Species richness (S) was higher in the Sudan-Sahel zone (6.53 ± 2.33) compared to Sudan (4.65±2.26) and Sahel zones (5.30±1.80) ($p<0.05$) (Figure 6.5). However, species richness did not differ much between the Sahel and the Sudan zone. The mean species richness at the farmland level (α diversity) reported in this study was lower (4.65±2.26 - 6.53±2.33) than the species richness in earlier research works. Balima et al. (2020) found a mean species richness of 8.97 for tropical West African AFS. Species richness in this research was also lower than the values obtained within *Vitellaria paradoxa* parklands in Ziro province (6±1 and 13±1) and Balé province (12±2 and 22±4), respectively (Dayamba et al., 2016). The difference in plot level species richness could be more explained by management practice adopted in each AFS. In this perspective, practice tending to systematically keep useful trees (fruits, fuelwood, medicine, fodder…) in West Africa AFS (Teklehaimanot, 2004) will increase species richness and carbon stock, unlike cropping intensification (cash crops including cotton (*Gossypium hirsutum*)).

Agroforestry systems (AFS) within Sahel (H=1.31 ± 0.36; D=0.66 ± 0.14) and Sudan-Sahel zones (H=1.26 ± 0.38; D=0.59 ± 0.16) showed higher tree diversity than in Sudan (H=0.91 ± 0.49; D=0.45 ± 0.23) zone ($p<0.05$). Neya et al. (2018) found lower diversity (lower value of Shannon's index) within the transition zone (Sudan-Sahel) (H=1.36), compared to the Sudan zone (H=1.71). These differences could result from the size of the sample area and communities. Furthermore, different Shannon's index values ranged between that obtained (H=0.81±0.27 and 2.45±0.22) within *Vitellaria paradoxa* parklands in Ziro and Balé provinces of Burkina Faso (Dayamba et al., 2016). Also, greater values were indicated by Ouinsavi and Sokpon (2008) (H=2.59 and 2.94), within Benin Republic AFS. The reason could be the difference in agricultural land management practices across West Africa that can contribute to species diversity conservation (Atta-Krah et al., 2004; Gebrewahid and Meressa, 2020) and the difference in climatic conditions such as the variation in moisture and nutrient availability (Nuberg et al., 2009).

The higher diversity of trees in the Sahel zone and the transition zone (Sudan-Sahel) compared to the Sudan zone, could be explained by the fact that farmers in a harsh environment (Sahel and Sudan-Sahel) with rare woody species in the residual bushes are less willing to cut trees on their farms, compared to areas where there are still enough trees in the natural forest. The reason is the conservation of useful species that are mostly threatened in the residual bushes. Another explanation for the lower farm tree diversity could be the clearing of large areas for cash crops (e.g. Cotton (*Gossypium hirsutum*) and sesame (*Sesamum indicum L.*)) in the Sudan zone, leaving only shea trees as mono-species tree stands.

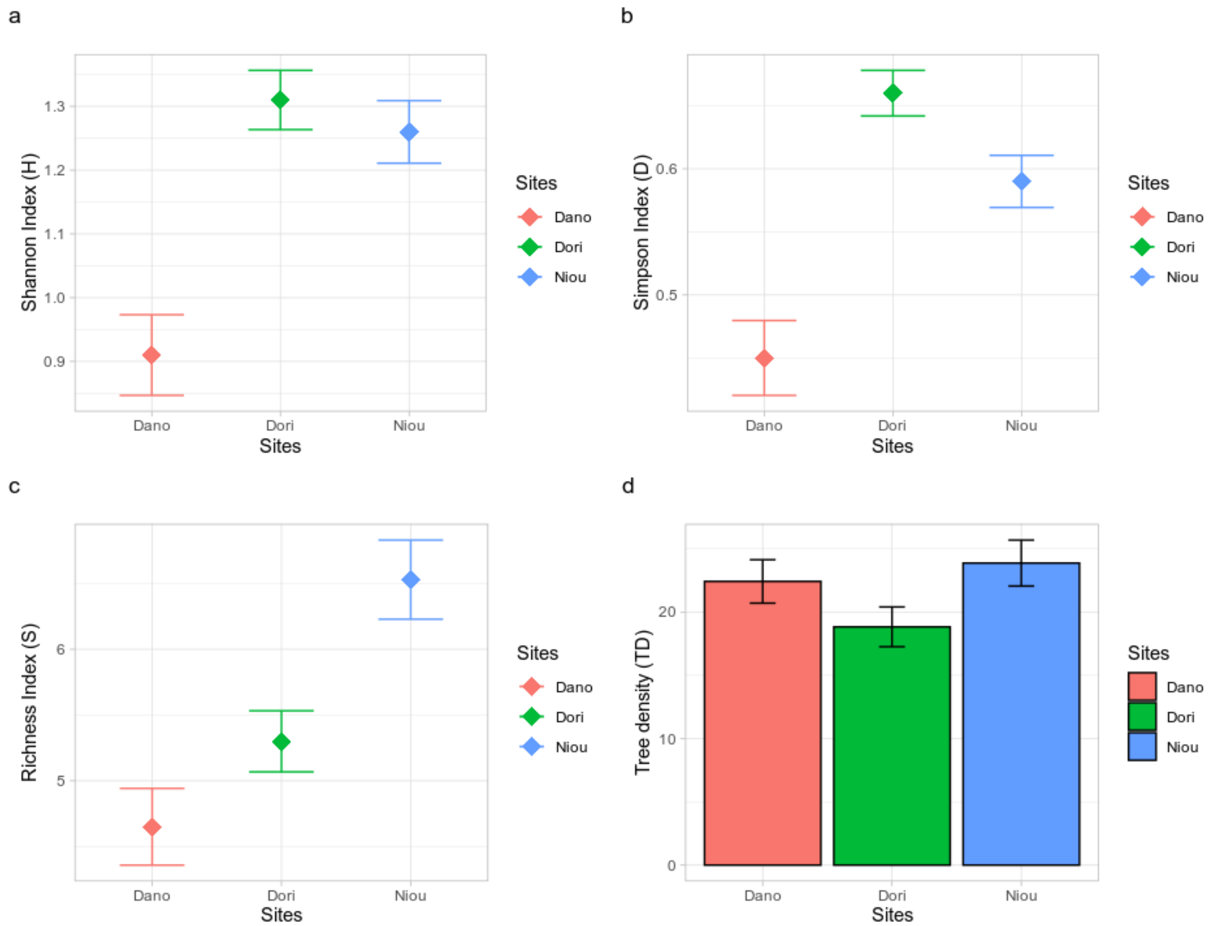


Figure 6.5: Variations in tree diversity and density across climatic zones. (a) Shannon's index, (b) Simpson's index, (c) Richness index, (d) Tree density. Source: author's Own computation, 2023.

#### 6.3.2.2 Above ground carbon sequestration within the mixed-crop-livestock system

Besides forests and residual bushes, AFS in Burkina Faso plays a significant role in carbon sequestration across the country, as reported by Ghimire and Bolakhe (2020). As we move from the Sahel to the Sudan climatic zone, the mean aboveground carbon stocks found in AFS varied from 3.4±2.2 to 8.1±4.1 Mg $C.ha^{-1}$ C/ha (Figure 6.6). These were within the range of carbon stocks (0.29 and 15.21 Mg C/ha) reported for West African AFS (Nair et al., 2009). Nevertheless, these values were lower than the carbon stock indicated by other authors in agroforestry farmlands in Burkina Faso: 12.65 ± 1.34 Mg C/ha (Balima et al., 2020); 6.73±1.59 to 9.23±1.59 Mg C/ha (Neya et al., 2020); 2.97±0.61 to 11.95±2.97 Mg C/ha (Dayamba et al., 2016). Also, they were lower than values in agroforestry farmlands within other Sub-Sahara African countries (5.17±1.10 to 11.49± 2.60 Mg C/ha (Gebrewahid and Meressa, 2020) and 6.5±0.1 to 12.4±0.1Mg C/ha (Henry et al., 2009). These observed differences in carbon density within AFS could be explained by farmers land management practices to cut or keep enough trees on their farmlands from one climatic zone to another, one country to another. Trees diversity and density positively influenced the carbon storage at the farm-scale across all the zones (Figure 6.7; Appendix 8). This aligned with previous literature (Bunker et al., 2005; Dayamba et al., 2016; Dimobe et al., 2019; Henry et al., 2009).

This interrelation between carbon density and plant biodiversity might be explained by the fact that the spatial distribution of both parameters is influenced by some environmental factors such as climate, topography, geology, soils and disturbance

(Talbot, 2010). The factors suitable for carbon density are likewise relevant to biodiversity and vice-versa (Dayamba et al., 2016). Crop-livestock integration contributes to this process since it is common to find tree seeds inside rumen of livestock (later found in dropping) that could contribute to farm biodiversity improvement (through manure fertilisation).

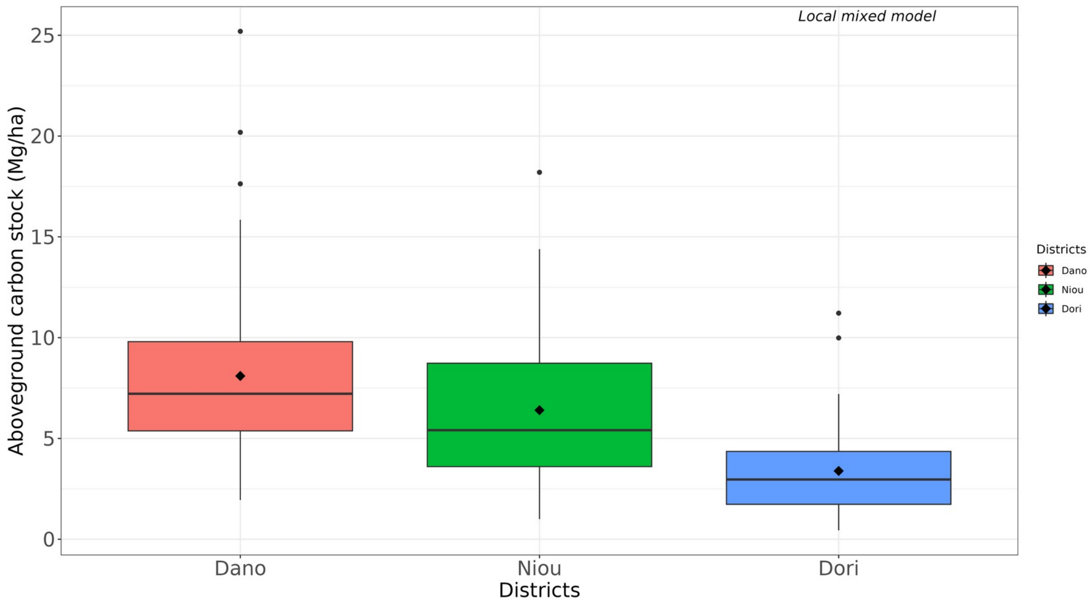


Figure 6.6: Variation in carbon density between climatic zones : Sudan (Dano), Sudan-Sahel (Niou) and Sahel (Dori). Source: author's Own computation, 2023.

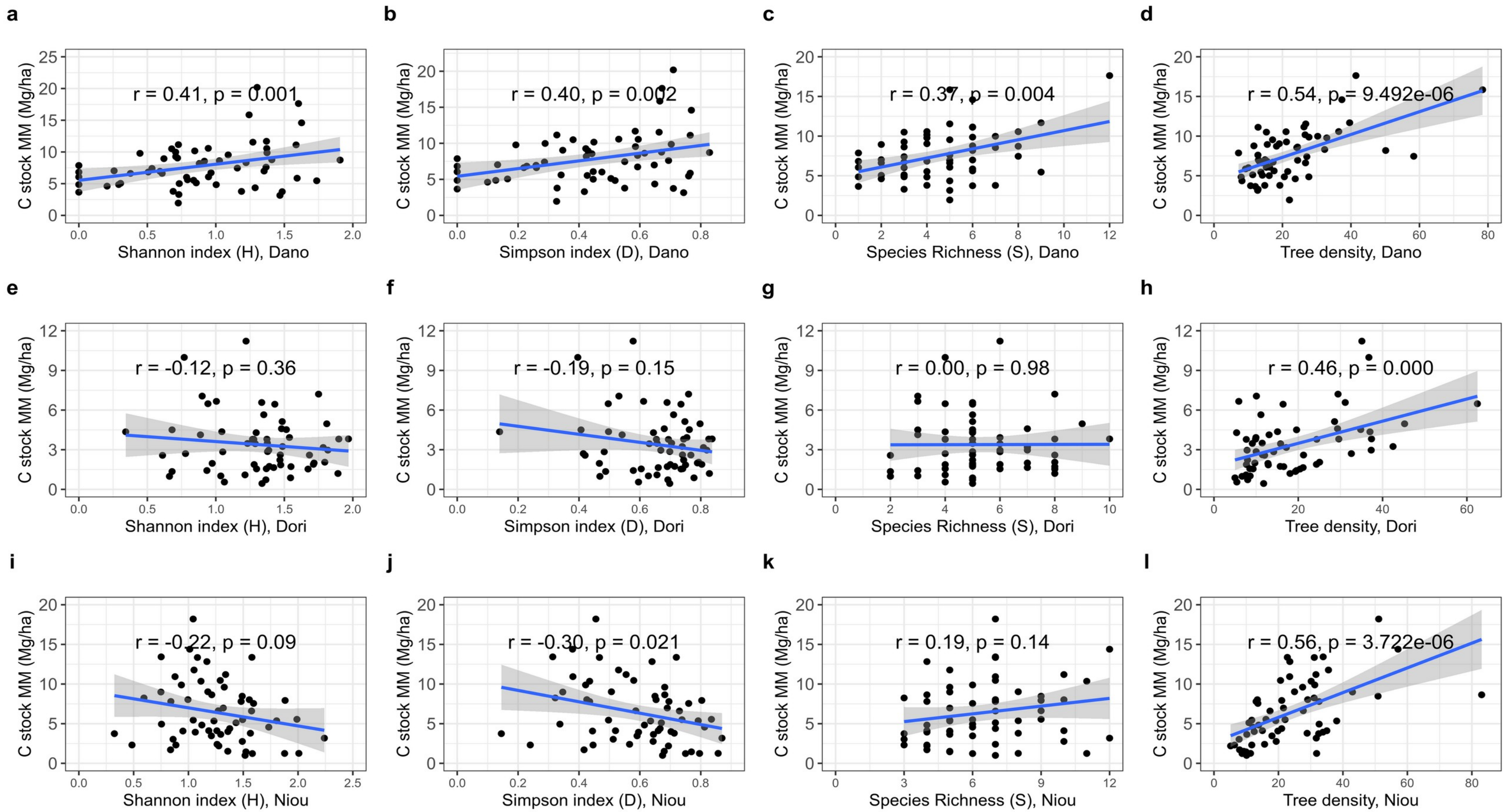


Figure 6.7: Correlation between carbon stock and woody species diversity in the Sudan (a to d), the Sudan-Sahel (e to h), and Sahel (i to l) zones of Burkina Faso following Mixed local model. C stock is the carbon stock and MM is the mixed model. Source: author's Own computation, 2023.

### 6.3.3 Water productivity

Water productivity is the crop or animal output per unit volume of water depleted. A few practices needed to ensure this efficiency include the reduction of water losses through evaporation, increasing soil water retention, the adequate use of virtual water in fodder and crop residues.

#### 6.3.3.1 Livestock feeding strategies

Within each climatic zone, the animal feed was mainly crop residues, natural pasture and agricultural by-products whose usage differs according to the seasons. Indeed, natural pastures constitute the main feed source (41-42 %, 27-33 %, 59-75 %) in Sudan (Dano), Sahel (Dori) and Sudan-Sahel (Niou) zones, respectively, for ruminant livestock (cattle, sheep, goat) in the wet season (Figure 6.8). Crop residues (cereal straw, legume residues, cow-pea pods) constitute the main feed sources during the dry season (57-75 %, 38-41 % and 71-74 %) in Sudan, Sahel and Sudan-Sahel, respectively. This aligned with previous findings within the Sudan-Sahel and Sahel zones of Burkina Faso (Amole et al., 2021). Besides that, agricultural by-products (1-3 %, 12-32 % and 3-9%) and fodder trees (6-24 %, 8-24 % and 1-3 %) in Sudan, Sahel and Sudan-Sahel, respectively are important feed sources across the seasons (Figure 6.8, 6.9, 6.10). Therefore, the ruminant's livestock feeding strategies across climatic zones rely on crop residues, natural pasture and agricultural by-products.

The highest contribution of crop residues to the feeding strategies in the Sudan zone is because many of these residues are often left in the field after harvest and freely accessible to mobile herds. The farmers leave about 80 % of cereal crop residues on their fields (Andrieu et al., 2015). Inversely, in the Sudan-Sahel zone, the collection and storage of crop residues are done to supplement the natural pasture from grazing lands. The Sahel zone presents the lowest contribution of crop residues in the feeding strategies. This is due to the comparatively lower crop residues biomass produced by farming systems. In such conditions, farmers must rely additionally on agricultural by-products (bran, grain, cotton seed cake etc.) in their feeding strategies. In all zones, crop residues are of greatest use during the dry season when the available pasture is low in quantity and quality (Amole and Ayantunde, 2019).

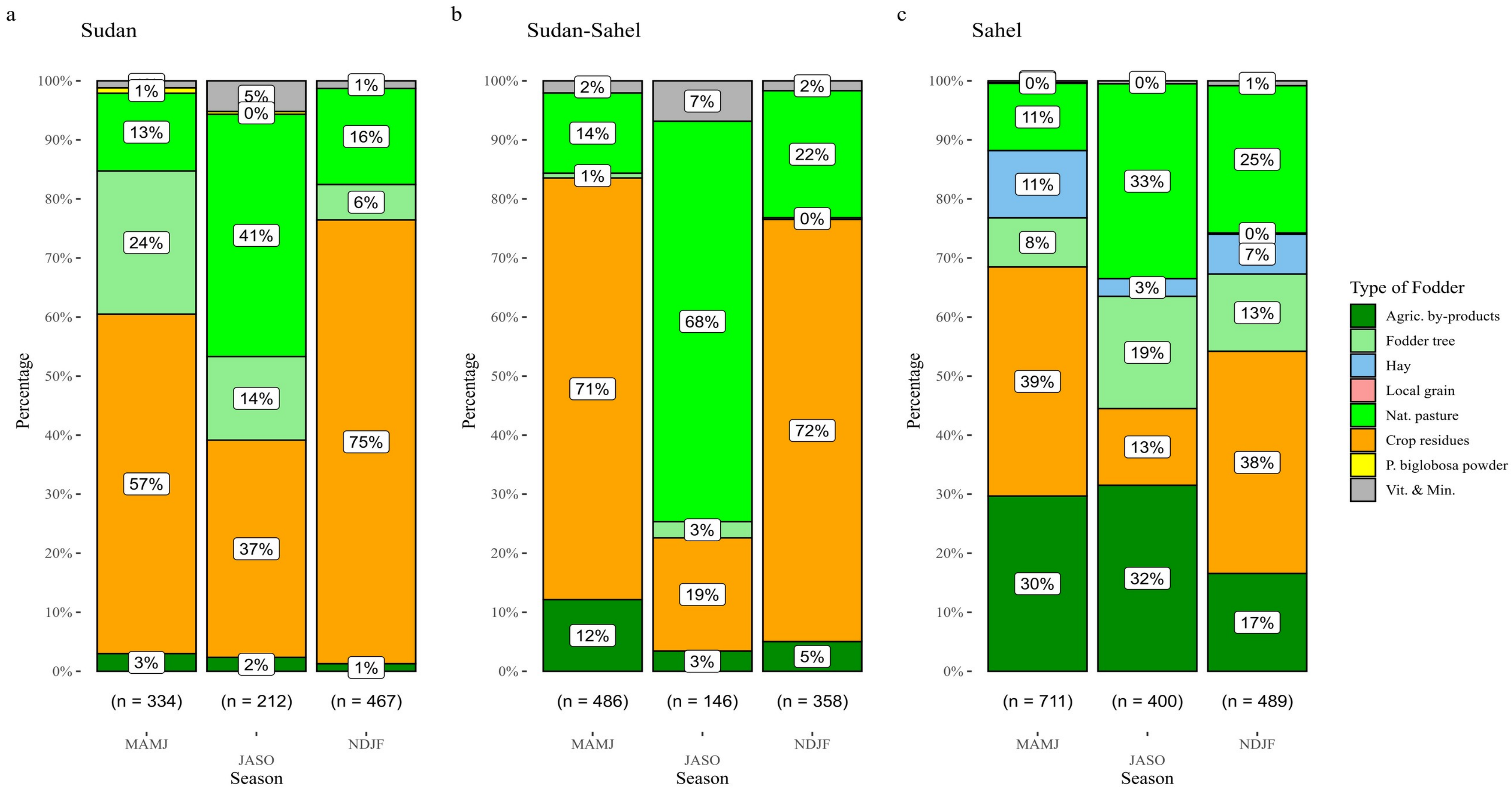


Figure 6.8: Feed sources available for cattle feeding across seasons and climatic zones of Burkina Faso. MAMJ: March-April-May-June; JASO: July-August-September-October; NDJF: November-December-January-February Source: author's Own computation, 2023.

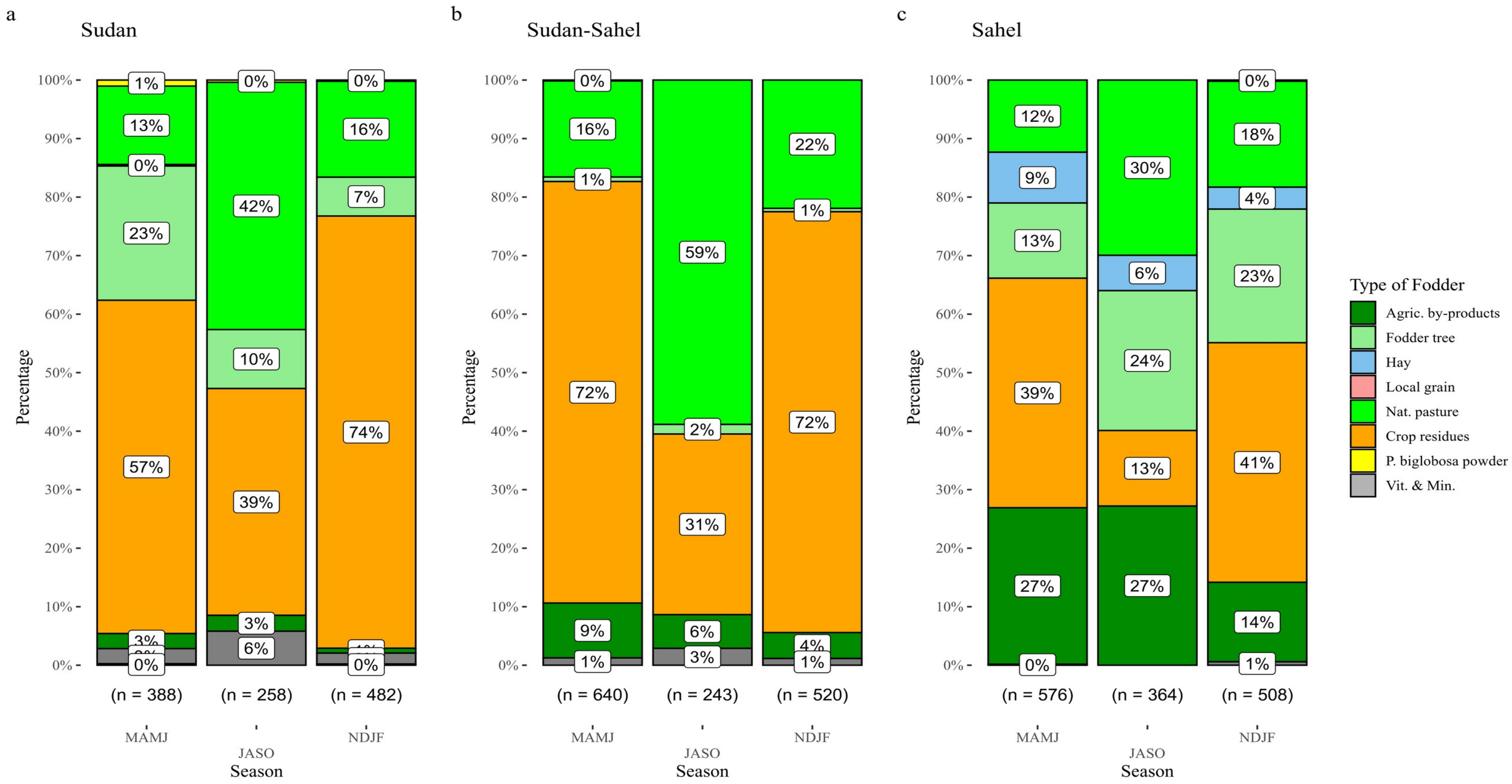


Figure 6.9: Feed sources available for sheep feeding across seasons and climatic zones of Burkina Faso. MAMJ: March-April-May-June; JASO: July-August-September-October; NDJF: November-December-January-February. Source: author's Own computation, 2023.

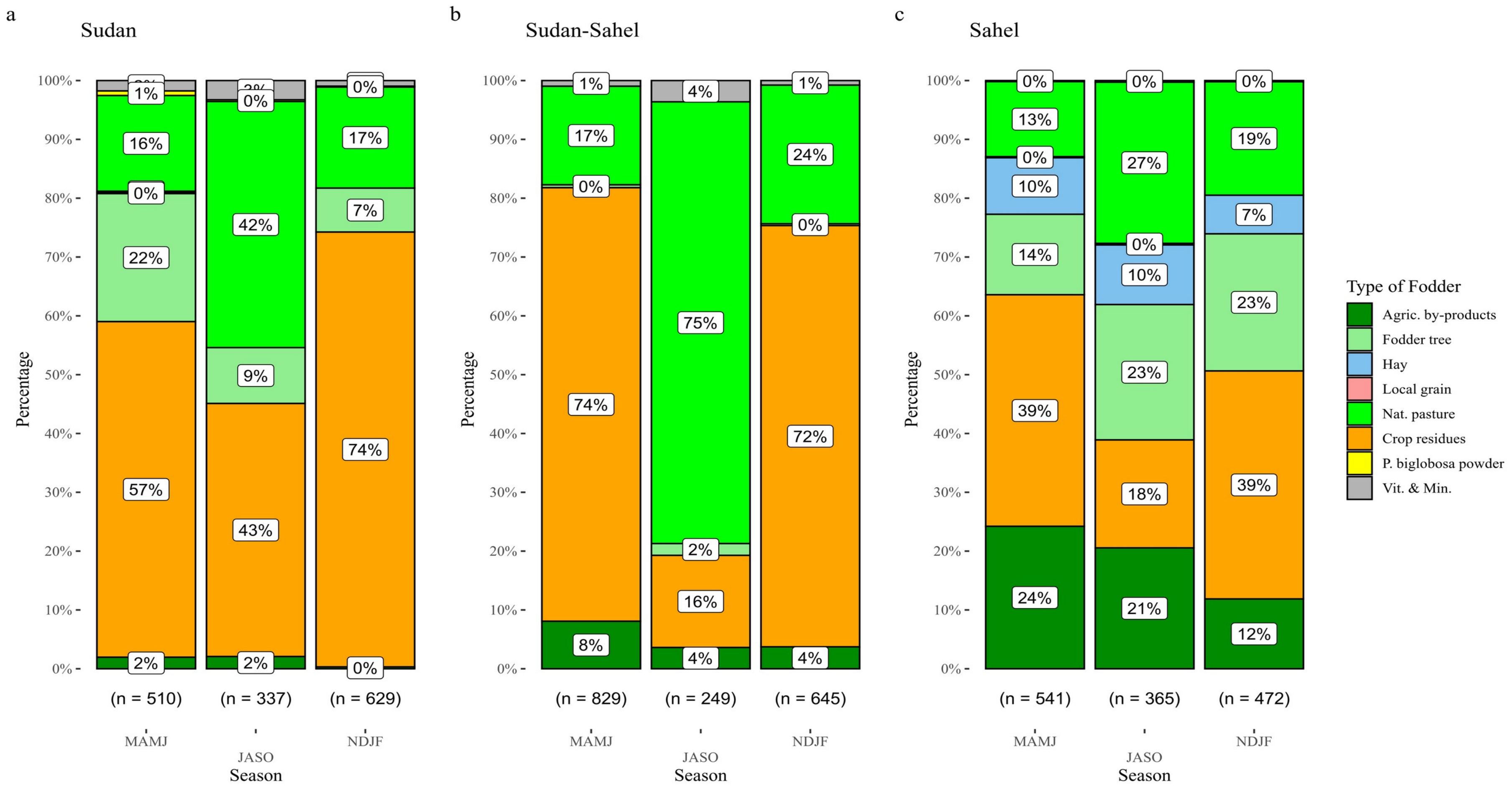


Figure 6.10: Feed sources available for goat feeding across seasons and climatic zones of Burkina Faso. MAMJ: March-April-May-June; JASO: July-August-September-October; NDJF: November-December-January-February. Source: author's Own computation, 2023.

Livestock feeding strategies and the production of livestock and crop induce important water losses mainly through evapotranspiration. These water losses need to be assessed for more insights on their use efficiencies within mixed-crop-livestock systems of water-stressed regions such as Burkina Faso.

#### 6.3.3.2 Water depleted in the mixed-crop-livestock system

The amount of water depleted is driven by the quantity produced of crop grain and livestock feed, including crop residues (maize, millet, sorghum, groundnut, and cowpea) and natural pasture from grazing lands. The amount of depleted water for crop production varied from 1,067.7±683.4 to 1,300.0 ± 177.9 $m^3$/ha/y and was higher ($p < 0.05$) in the Sahel zone (Figure 6.11). The depleted water for livestock feed production varied from 1,748.9 ± 945.0 to 2,852.4 ± 798.9 $m^3$/ha/y and was also higher in the Sahel ($p < 0.05$). This situation could be explained by the high evaporation potential that characterise Sudan-Sahel and Sahel zones comparatively to the Sudan zone.

The amount of water depleted for both crop and feed production is so important that its valuation can suitably be done through crop-residues uses in the mixed-crop-livestock farming system.

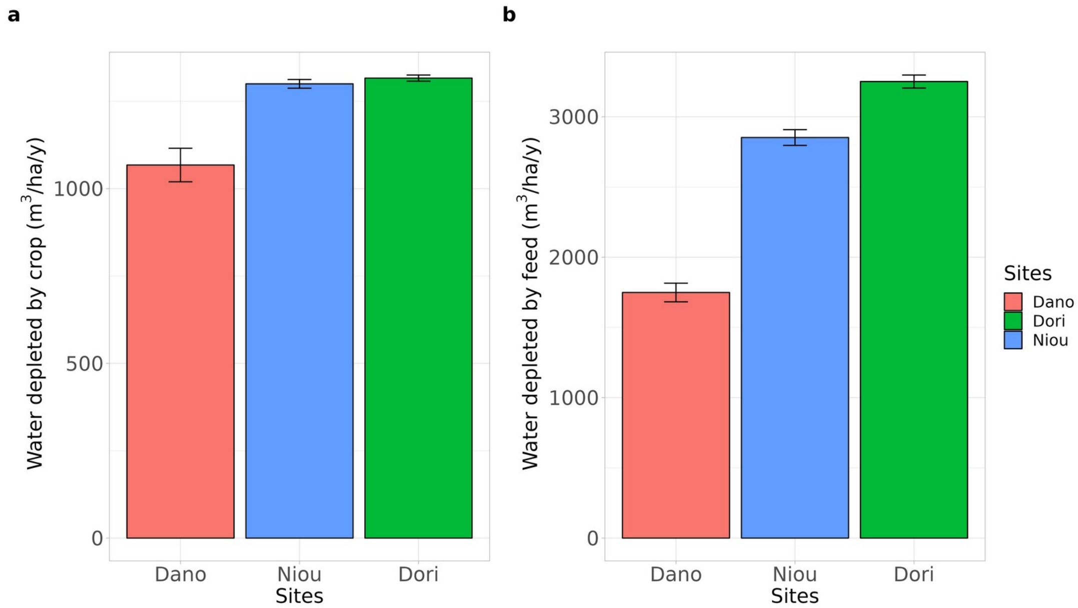


Figure 6.11: Water depleted ($m^3$/ha/y) by crop (a) and livestock feed (b) productions across climatic zones. Source: author's Own computation, 2023.

#### 6.3.3.3 Crop-livestock beneficial outputs

Both physical and financial crop outputs per household per annum was higher (2,723.3±158.5 kg/household/y and 1,140.5±1056.8US$/household/y) in the Sudan zone (P<0.05) (Table 6.4). Livestock financial outputs were in the range 710.2±42.8 – 1,228.2±83.7 US$/household/y. This compared well with 679.9±75.6 – 1,436.1±63.7 US$/household/y reported for mixed-crop-livestock farming in Ethiopia (Abebe, 2012).

The quantity and value of milk produced (160.3±13.5 l/TLU/y and 136.8 ±122.8 US$/household/y) in the Sahel zone were the highest (P< 0.05) (Table 6.5). Values for manure (187.21±172.06 US$/household/y), livestock services (285.2±220.5 US$/household/y), and quantity and value of meat (333.1±213.3 kg/household/y and 752.8 ± 672.9 US$/household/y) from the Sudan zone were higher (P<0.05) than those from Sudan-Sahel and Sahel zones (Table 6.5). The values obtained in the Sahel zone for the same type of farmers (Sedentary extensive), were all comparatively higher than those indicated by Amole et al. (2021) in the same zone for milk (2.18 US$/household/y), livestock off-take (136.2 US$/household/y), manure (1.8 US$/household/y), services (1.2 US$/household/y). Similarly, for the Sudan-Sahel zone, Amole et al. (2021) reported lower values for livestock off-take (98.2 US$/household/y), manure (2.1 US$/household/y), services (25.6 US$/household/y).

From livestock manure production, the results showed a significant difference ($P<0.05$) in the amount of nitrogen ($N_{dung}$) and potassium ($K_{dung}$) made available through livestock dropping across zones. For the phosphorus ($P_{dung}$), a significant difference was found only between Sudan and the two other zones (Sudan-Sahel and Sahel) (Table 6.6).

Table 6.4: Crop-livestock beneficial outputs per household across climatic zones.

| Zones | Crop output (kg/household /year) | Crop output (US$/household /year) | Livestock output (US$/household /year) | Total output (US$/household /year) |
|---|---|---|---|---|
| Sudan (Dano) | 2,723.3±158.5[a***] | 1,031.3±71.5[a***] | 1,228.2±83.7[a***] | 2,152.3±116.5 |
| Sudan-Sahel (Niou) | 1,406.0±59.5[b***] | 606.7±27.1[b***] | 820.5±39.8[b***] | 1,429.8±56.4 |
| Sahel (Dori) | 1,779.4±80.7[c***] | 825.8±37.1[c***] | 710.2±42.8[c***] | 1,532.9±68.2 |

Means±sd error with different superscripts along the columns differ significantly. Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 . Source: author's Own computation, 2023.

Table 6.5: Detailed livestock beneficial outputs per household across climatic zones

| Zones | Services (US$/household/y) | Manure (US$/household/y) | Milk (l/TLU/y) | Milk (US$/household/y) | Meat (kg/household/y) | Meat (US$/household/y) |
|---|---|---|---|---|---|---|
| Sudan (Dano) | 285.2±220.5[a***] | 187.2±172.1 [a***] | 7.2±3.1[a***] | 12.7±1.8[a***] | 333.1±213.3[a***] | 752.8±672.9[a***] |
| Sudan-Sahel (Niou) | 198.4±133.8[b***] | 111.6±98.0[b***] | - | - | 206.8±126.3[b***] | 498.3±399.9[b***] |
| Sahel (Dori) | 82.7±82.0[c***] | 111.7±93.1[b***] | 160.3±13.5[b] | 136.8±122.8[b***] | 146.2±94.3[c***] | 431.3±371.2[c***] |

Means±sd error with different superscripts along the columns differ significantly. Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Source: author's Own computation, 2023.

Table 6.6: Potential fertilisation per tropical livestock unit (kg/TLU/year) across the climatic zones

| Zones | $N_{dung}$ | $P_{dung}$ | $K_{dung}$ |
|---|---|---|---|
| Sudan (Dano) | $6.3 \pm 0.1^{a***}$ | $2.5 \pm 0.0^{a***}$ | $20.0 \pm 0.4^{a***}$ |
| Sudan-Sahel (Niou) | $7.0 \pm 0.1^{b***}$ | $2.6 \pm 0.0^{b***}$ | $22.5 \pm 0.7^{b***}$ |
| Sahel (Dori) | $5.8 \pm 0.1^{c***}$ | $2.5 \pm 0.0^{b***}$ | $17.9 \pm 0.3^{c***}$ |

Means±sd error with different superscripts along the columns differ significantly. Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Source: author's Own computation, 2023.

The quantification and valuation of crop and livestock beneficial outputs and their corresponding depleted water enabled the computation of crop and livestock water productivity in the subsequent section.

#### 6.3.3.4 Crop-livestock water productivity

With higher returns from the crop-livestock beneficial output, physical crop water productivity (0.40±0.02 kg/$m^3$) and financial livestock water productivity (0.17±0.01 US$/$m^3$ ) were the highest in the Sudan zone ($p < 0.05$). Likewise, the highest total water productivity (TWP) (0.29±0.01 US$/$m^3$) was experienced in the Sudan zone ($p < 0.05$). However, despite the highest return of crop output in Sudan, the highest financial crop water productivity (0.16±0.01 US$/$m^3$) was experienced in the Sahel zone. It differed significantly from that of Sudan (0.15±0.01US$/$m^3$) and Sudan-Sahel (0.13±0.01 US$/$m^3$) zones (Figure 6.12). Lower values of LWP were experienced in the Sudan-Sahel (0.09±0.01 US$/$m^3$) and Sahel (0.06±0.01US$/$m^3$) zones. Similarly, lower physical crop water productivity was experienced within Sudan-Sahel (0.29±0.01 kg/$m^3$) and Sahel (0.33±0.01 kg/$m^3$) zones (Figure 6.12).

The findings on crop-livestock water productivity compared well with those of previous literature. Indeed, LWP experienced across climatic zones revealed an increasing trend (0.06±0.01 US$/$m^3$ to 0.17±0.01 US$/$m^3$) from the Sahel to the Sudan zone. The values in the Sudan-Sahel (0.09±0.01 US$/$m^3$) and Sahel (0.06±0.01US$/$m^3$) zones were similar to those of 0.06 to 0.08 US$/$m^3$ reported by (Mekonnen et al., 2011) in Ethiopia and 0.01 to 0.11 US$/$m^3$ reported by Amole et al. (2021) across the same zones of Burkina Faso. Also, the LWP obtained in the Sudan zone (0.17±0.01US$/$m^3$) was quite similar to the average value (0.16 ±0.01 US$/$m^3$) indicated by (Abebe, 2012) and within the range (0.1 and 0.6 US$/$m^3$) indicated by (Haileslassie et al., 2009a, 2009b) in Ethiopia.

Financial CWP (0.13±0.01 to 0.16±0.01US$/$m^3$) was found to be lower than those reported in Ethiopia by Haileslassie et al. (2009b) (0.24-0.38 US$/$m^3$) and Haileslassie et al. (2009a) (0.2-0.5 US$/$m^3$). Likewise, the physical CWP (0.29±0.01 to 0.40 ± 0.02 kg/$m^3$) across climatic zones was quite similar to the findings 0.24 - 0.38 kg/$m^3$ by Haileslassie et al. (2009b) and 0.3 - 0.5 kg/$m^3$ by Haileslassie et al. (2009). Kima et al. (2020) and Bama et al. (2020) respectively reported higher CWP values of 0.41 kg/$m^3$ and 0.85 kg/$m^3$ within rice-based systems in Burkina Faso. There are possibilities to improve crop water productivity across the three climatic zones of Burkina Faso. Increasing CWP means improving the LWP of the mixed-crop-livestock farming systems across zones through increased availability of crop-feeds (straw and by-products) for livestock use. Well-fed livestock will have higher output (milk and meat, manure, traction) through higher use efficiency of transpired water.

Milk water productivity varied from 0.004±0.004 l/$m^3$ to 0.02±0.01 l/$m^3$ within Sudan and Sahel zones, respectively. Meat water productivity amounted to 0.04±0.03

kg/$m^3$ in Sudan, 0.02±0.01 kg/$m^3$ in the Sudan-Sahel and 0.01±0.01 kg/$m^3$ in the Sahel zone (Figure 6.12). Milk and meat water productivity across climatic zones were all lower than those (1.0 l/$m^3$, 0.09 kg/$m^3$) reported by Gebreselassie et al. (2009) in Ethiopia.

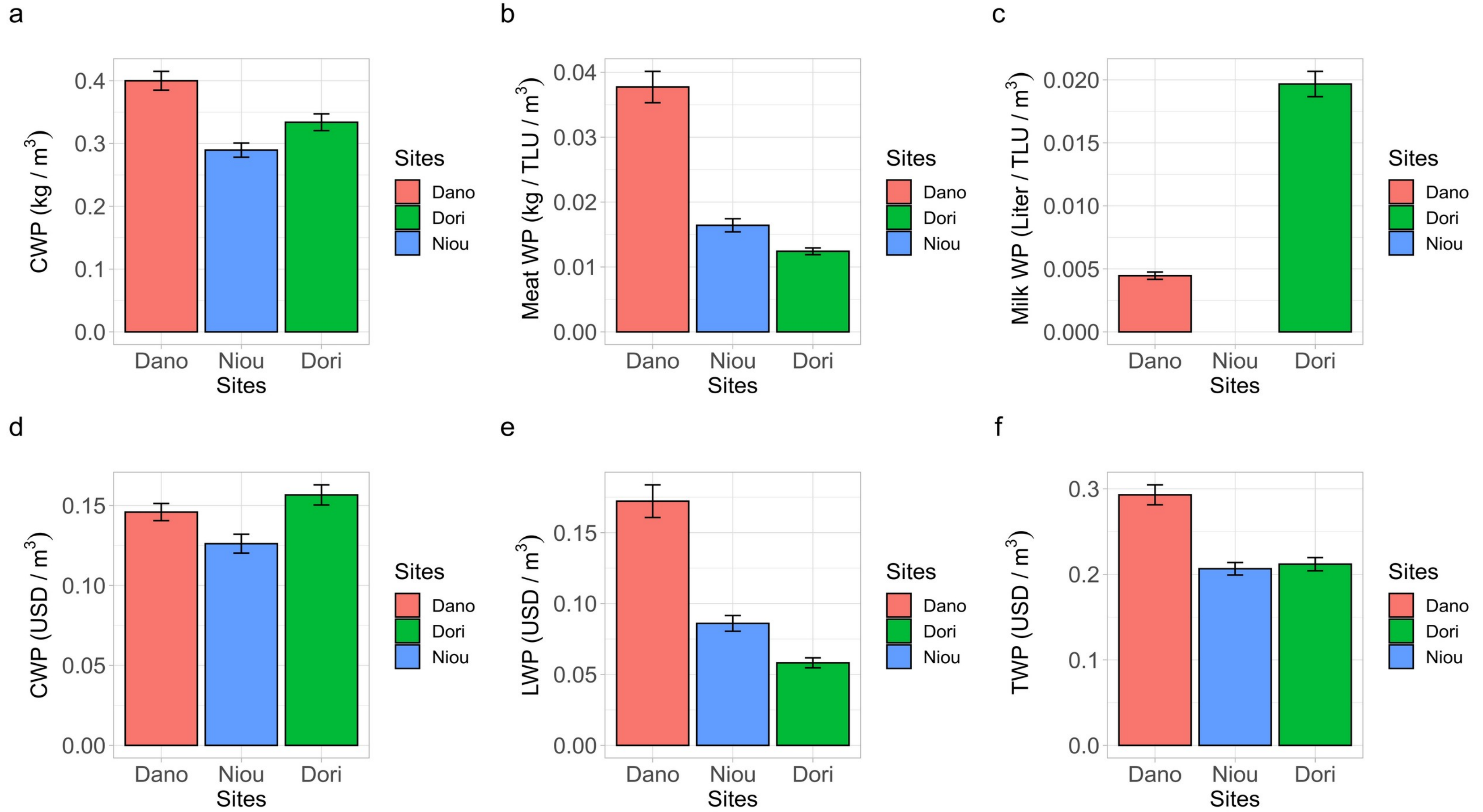


Figure 6.12: Crop-livestock physical (kg/m3±sd error) and financial (US$/m3±sd error) water productivity across climatic zones of Burkina Faso. Legend: CWP: Crop Water Productivity, LWP: Livestock Water Productivity. TWP: Total Water Productivity. Source: author's Own computation, 2023.

Crop-water productivity among other factors is also highly dependent of soils physical and chemical properties specially its nutrient contents. The subsequent section will examine soil characteristics within the mixed crop-livestock system.

### 6.3.4 Soils properties and carbon sequestration

#### 6.3.4.1 Soil pH and nutrients

Soil pH and nutrient results are presented in Table 6.7. Soil pH was estimated at 5.4±0.5 and 5.4±0.3 within the Sudan-Sahel and Sudan zones, respectively and differed significantly from one zone to the other ($p < 0.05$). Based on Sys's (1993) findings, the pH levels of these soils were not found to be a significant constraint for crop cultivation in the two zones. The percentage of Nitrogen (N) in the 20 cm top soil differed significantly between the Sudan zone (0.09±0.03) % and Sudan-Sahel zone (0.08±0.01) %. Thus, nitrogen did not constitute a limiting factor in soil fertility across the two zones (Dabin, 1956; Sys et al., 1993). The amount of phosphorous significantly differed between zones and was estimated at 2.5±0.6 and 3.9±3.9 mg/kg (0.008±0.001 and 0.013±0.01 cmol/kg) within Sudan-Sahel and Sudan zones respectively. The phosphorous also did not constitute a limiting factor of soil fertility with regards to the required level of phosphorus in fertile soil (Dabin, 1956; Sys et al., 1993). On the contrary, the assimilable potassium constituted a severe limiting factor to soil fertility across the two zones. Potassium that also significantly differed between zones was estimated at 75.9±29.1 and 71.8±47.7 mg/kg (0.19±0.07 and 0.18±0.07 cmol/kg). These amounts were far below the required amount for high (0.3-0.4 cmol/kg) and very high (> 0.4 cmol/kg) soil fertility (Dabin, 1956; Sys et al., 1993). It can be concluded that soil fertility and therefore crop water productivity across zones could be limited by soils' potassium content. This deficit must be corrected to sustain soil fertility and food security across the studied zones.

Table 6.7: Soil pH and nutrients across climatic zones

| Districts | Soil pH | N (%) | P (mg/kg) | K* (mg/kg) |
|---|---|---|---|---|
| Dano (Sudan) | 5.4±0.3[a] | 0.09±0.03[a] | 3.9±3.9[a] | 71.8±47.7[a] |
| Niou (Sudan-Sahel) | 5.4±0.5[b] | 0.08±0.01[b] | 2.5±0.6[b] | 75.9±29.1[b] |
| Dori (Sahel) | - | - | - | - |

Mean±sd values in the same column followed by different superscripts differ significantly at $p<0.05$.
* Soils potassium content is a major limitation of soils fertility within the Dano (Sudan) and Niou (Sudan-Sahel); Due to security reasons, data could not be taken in the Sahel zone. Source: author's Own computation, 2023.

#### 6.3.4.2 Soil bulk density and organic carbon

Soil bulk density, carbon percentage, and stocks were also higher in the Sudan zone than in the Sudan-Sahel zone ($p < 0.05$). The mean bulk densities for total depth 0–20 cm increased from 1.54±0.15 Mg/m$^3$ in the Sudan-Sahel zone to 1.60±0.15 Mg/m$^3$ in the Sudan zone ($p < 0.05$). Similar increases were observed for carbon concentration (0.81±0.16 % to 1.16±0.41 %) and carbon stock (12.4±2.8 Mg/ha to 18.7±7.5 Mg/ha) as one moved from Sudan-Sahel to the Sudan zone ($p < 0.05$). It appears that soils in the Sudan zone are heavier and rich in carbon than those in the Sudan-Shel zone. This indicates a higher carbon sequestration potential in the Sudan than in the Sudan-Sahel zone. This could have contributed to the observed higher crop water productivity within the Sudan zone (Table 6.8; Figure 6.13). Carbon stock in the Sudan-Sahel zone is close to that (12 Mg/ha and 14 Mg/ha) obtained by Youl et al. (2011) within two cropping systems of South-West (Sudan zone) Burkina Faso.

Inversely, these values were lower than that observed in the Sudan zone (18.7 ± 7.5 Mg/ha) in the current study. Differences in land management practices could be a reason. Moreover, Dayamba et al. (2016), from their study within the Southern Sudan-Sahel zone of Burkina Faso (Balé and Ziro provinces), found similar results. These authors revealed that the standardized value of soil carbon stock for every 10 cm of soil in depth 0–20 cm in Ziro, was 12.17 ± 0.37 Mg/ha while in Balé, it was 10.68 ± 0.31 Mg/ha. Thus the whole 0-20 cm amounted to about 21.6 to 24.4 Mg/ha of carbon stock within Ziro and Balé croplands, respectively.

Table 6.8: Soil bulk density and organic carbon

| Districts | Bulk density ($Mg/m^3$) | C (%) | SOC (Mg/ha) |
|---|---|---|---|
| Dano (Sudan zone) | $1.60 \pm 0.15^a$ | $1.16 \pm 0.41^a$ | $18.7 \pm 7.5^a$ |
| Niou (Sudan-Sahel) | $1.54 \pm 0.15^b$ | $0.81 \pm 0.16^b$ | $12.4 \pm 2.8^b$ |
| Dori (Sahel) | - | - | - |

Mean values in the same column followed by different superscripts differ significantly at $p<0.05$. Source: author's Own computation, 2023.

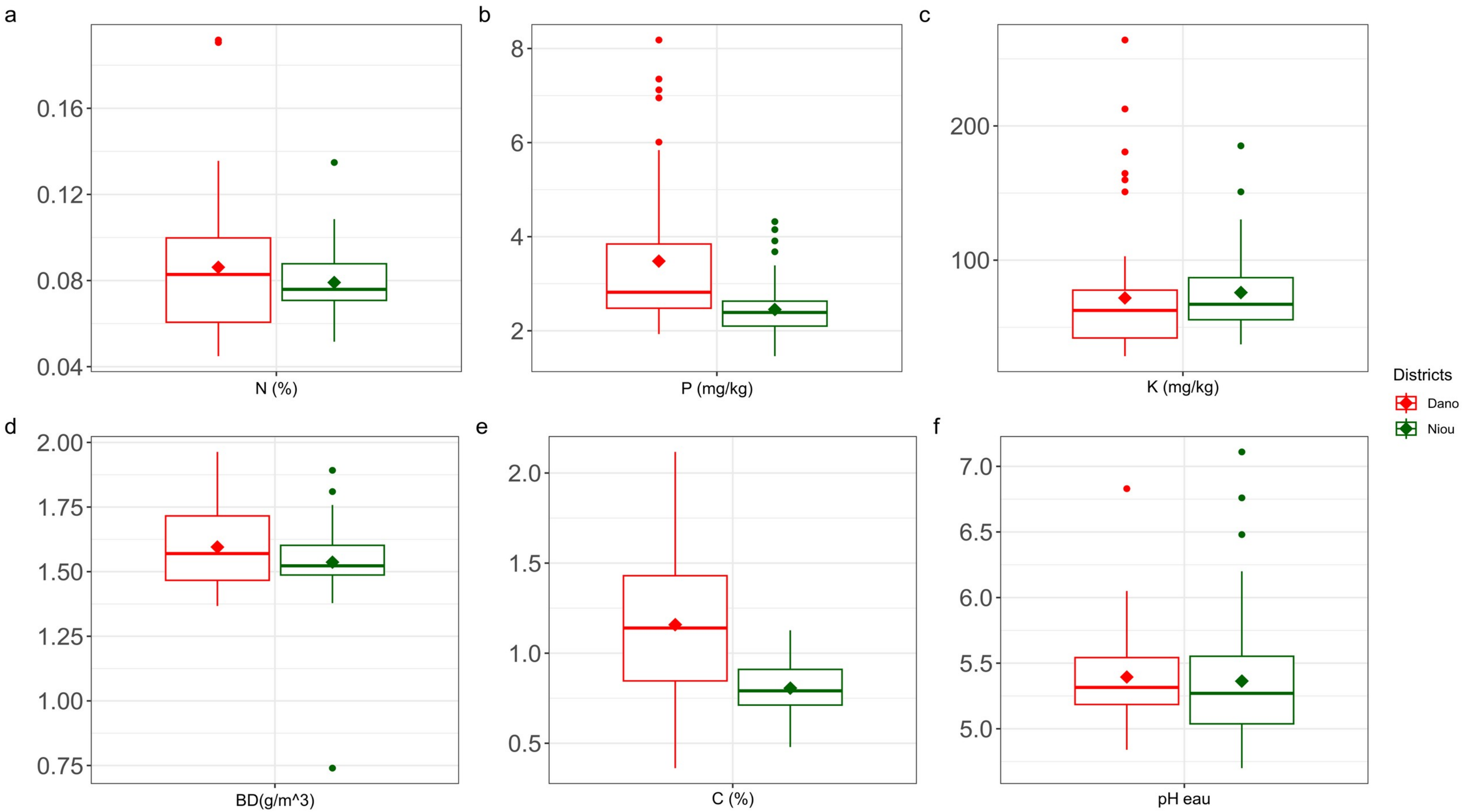


Figure 6.13: Soil properties and organic carbon content in Sudan and Sudan-Sahel zones. (a) N: Nitrogen, (b) P: Phosphorus assimilable, (c) K: Potassium, (d) BD: Bulk Density, (e) C: Carbon, (f) pH eau. ♦: mean value. Source: Author's Own computation, 2023.

#### 6.3.4.3 Relationship between soil nutrients and the inputs from dung and chemical fertilizers

From the correlation matrix (Table 6.9), soil fertility in Sudan and Sudan-Sahel is more dependent on chemical fertilizers inputs (NPK) than animal manure inputs. That explained why the integration indicators, namely, manure coverage needs moderately but significantly associated with soil nutrient content. This also explained the moderate association with farm productivity. Indeed, although both dung ($N_{dung}$) and chemical ($N_{ch}$) inputs of nitrogen did not significantly influence soil nitrogen ($N_{soil}$), soil Phosphorus ($P_{soil}$) and Potassium ($K_{soil}$) contents were rather significantly associated with chemical ($P_{ch}$, $K_{ch}$) inputs than they are with dung ($P_{dung}$, $K_{dung}$) inputs. Nevertheless, the contribution of manure in the recycling processes at the farm level is not negligible. This is in line with Agboola and Kintomo (1995), who reported significant recycling of P and K through animal faeces.

Table 6.9: Correlation matrix of soils, dung and chemical fertilizers nutrients contents

| Variables | $C_{soil}$ | $pH_{water}$ | $N_{soil}$ | $P_{soil}$ | $K_{soil}$ | $N_{ch}$ | $P_{ch}$ | $K_{ch}$ | $N_{dung}$ | $P_{dung}$ | $K_{dung}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $C_{soil}$ | 1 | | | | | | | | | | |
| $pH_{water}$ | 0.08 | 1 | | | | | | | | | |
| $N_{soil}$ | 0.77*** | 0.07 | 1 | | | | | | | | |
| $P_{soil}$ | 0.48*** | 0.24** | 0.31*** | 1 | | | | | | | |
| $K_{soil}$ | 0.39*** | 0.48*** | 0.41*** | 0.47*** | 1 | | | | | | |
| $N_{ch}$ | 0.29** | 0.07 | **0.16**· | 0.54*** | 0.32*** | 1 | | | | | |
| $P_{ch}$ | 0.20* | 0.03 | 0.07 | **0.39***** | 0.21* | 0.95*** | 1 | | | | |
| $K_{ch}$ | 0.20* | 0.03 | 0.07 | 0.39*** | **0.21*** | 0.95*** | 1.0*** | 1 | | | |
| $N_{dung}$ | 0.26** | 0.03 | **0.17**· | 0.39*** | 0.15·· | 0.50*** | 0.46*** | 0.46*** | 1 | | |
| $P_{dung}$ | 0.26** | 0.01 | **0.16**· | **0.36***** | 0.13 | 0.48*** | 0.44*** | 0.44*** | 0.98*** | 1 | |
| $K_{dung}$ | 0.26** | 0.04 | **0.17**· | 0.41*** | **0.17**· | 0.51*** | 0.46*** | 0.46*** | 0.99*** | 0.99*** | 1 |

$N_{soil}$, $P_{soil}$, $K_{soil}$ are N, P, K concentration in soil; $N_{ch}$, $P_{ch}$, $K_{ch}$ are N, P, K from chemical fertilizer; $N_{dung}$, $P_{dung}$, $K_{dung}$ are N, P, K from dung. Source: Author's Own computation, 2023.

### 6.3.5 Greenhouse gases balance in mixed crop-livestock systems

While farm-scale activities generate greenhouse gases ($CO_2$, $CH_4$, $N_2O$) into the atmosphere (Tongwane and Moeletsi, 2018), their removal is done through above-ground, below-ground and soil carbon sequestration.

Across zones, the amount of carbon dioxide sequestrated through biomass (above and below-ground sequestration) varied significantly, following a decreasing trend from Sudan to the Sahel zone. Indeed, the total carbon dioxide removed from the atmosphere through plant growth amounted 47.5±25.8, 37.5±28.6 and 20.6±13.4 Mg $CO_2$ in the Sudan, Sudan-Sahel and Sahel zones, respectively. Besides biomass sequestration, agricultural soils revealed a good reservoir for carbon, contributing thus to carbon dioxide removal from the atmosphere. Soil sequestration accounted for 59.2±30.3 Mg $CO_2$/household/y and 90.2±54.9 Mg $CO_2$/household/y within Sudan-Sahel and Sudan zones, respectively. The balance between emission and sequestration by trees' biomass were estimated at 15.0±13.9, 30.6±29.5 and 14.0±13.7 Mg CO2/household/year within Sudan, Sudan-Sahel and Sahel zones respectively. Finally, the balance between emission and sequestration by the combined trees biomass and soils were estimated at 122.6±75.3 and 89.8±51.9 Mg $CO_2$ /household/y within Sudan and Sudan-Sahel zones, respectively. A positive total budget in greenhouse balances was obtained regarding the sources and type of GHG emitted in the farming systems across zones. This means a higher sequestration (in biomass and soil) than emission. This is corroborated by Ortiz-Gonzalo et al. (2017) who indicated that together, soils and plant biomass can offset 25-36% of farm emissions. It can therefore be concluded that the current farming systems in some extent, are supporting mitigation and sustainable agriculture (Table 6.10). Overall, agricultural soils play an important role in greenhouse gas balance in smallholders mixed-cropping systems. On a yearly basis, soils sequester a higher quantity of carbon dioxide than trees' biomass, but in the long run the sequestration is more stable in trees than in soils. Indeed, agricultural soils are easily disturbed by farming practices and are therefore more prone to release sequestrated carbon easily.

Table 6.10: Farm scale balance of carbon dioxide (Mg CO2 /household /year) across climatic zones

| Districts | Aboveground carbon sequestration ($AGC_{Seq}$) | Belowground carbon sequestration ($BGC_{Seq}$) | Trees carbon sequestration ($TC_{Seq}$) | Soil carbon sequestration ($Soil_{Seq}$) | Emission | Balance 1 | Balance 2 |
|---|---|---|---|---|---|---|---|
| Dano (Sudan zone) | 37.6±21.0[a] | 9.8±4.8[a] | 47.5±25.8[a] | 90.2±54.9[a] | 15.0±13.9[a] | 32.4±30.5[a] | 122.6±75.3[a] |
| Niou (Sudan-Sahel zone) | 29.7±23.2[b] | 7.8±5.4[b] | 37.5±28.6[b] | 59.2±30.3[b] | 6.9±5.5[b] | 30.6±29.5[b] | 89.8±51.9[b] |
| Dori (Sahel zone) | 16.0±10.7[c] | 4.6±2.7[c] | 20.6±13.4[c] | - | 8.8±7.2[c] | 14.0±13.7[c] | - |

$TC_{Seq} = AGC_{Seq} + BGC_{Seq}$; Balance 1: $TC_{Seq.}$ - Emissin; Balance 2: ($TC_{Seq.}$ + $Soil_{Seq.}$) - Emission. Mean values in the same column followed by different superscripts differ significantly from each other at $p<0.05$. Source: author's Own computation, 2023.

This chapter's previous sections gave an overview of farm-scale emission, stem carbon sequestration potential, water productivity, soil carbon storage and fertility within the integrated crop-livestock system across climatic zones of Burkina Faso. How are these emissions, sequestration, productivity and soil fertility interrelating with the crop-livestock integration and to which extent? The subsequent sections of the chapter highlighted the potential implication of such mixed farming for farm-scale soil fertility and productivity, farm-scale emissions and mitigation potential. This provides an overview of how the integration of crops and livestock has the potential to enhance the resilience of farmers and farming systems.

### 6.3.6 Role of crop-livestock integration in farmers resilience

The resilience of each farmer's household is built on his ability to protect and secure its livelihood in a sustainable way to face the changing climate. This is fulfilled through a productive system with fertile soils and good potential of atmospheric carbon dioxide sequestration. It is in this perspective that Novak and Fiorelli (2010), indicated that mitigation measures might either reduce or prevent the emissions of GHG at the source, or favour the storage of carbon in plants or soils. This section of the work revealed how the integrated crop-livestock system can contributes to both emission and mitigation of greenhouse gases and how the system supports productivity and soil fertility enhancement.

#### 6.3.6.1 Crop-livestock integration and greenhouse gases emission

Table 6.11 gives an overview of the interrelations between integration indicators and farm-level greenhouse gases emissions. Across zones, farm-scale total emissions of carbon dioxide equivalent ($TCO_{2e}$) positively and significantly correlated with the coverage of draft-power needs (CoDPN) ($0.2 < r < 0.4$, $p < 0.05$). However, the total emissions significantly correlated with the coverage of manure needs (CoMN) ($r = 0.3$, $p < 0.05$) and the integration effectiveness (IE) ($r = 0.4$, $p < 0.05$), only in the Sudan zone. This could be explained by the fact that cropland fertilisation strategies rely mainly on farmer-owned herd in the Sudan zone, implying co-increases in both manure produced and emissions (from enteric fermentation and manure) as herd size increases. Unlike this zone, within the Sahel and Sudan-Sahel zone, beyond manure self-produced by farmers' herds, the fertilisation involved additional (out-farm) manure collection (Plate 6.3) from grazing lands and around watering points (manure from other herds). This could explain the insignificant association of the coverage of farm manure needs to the size of herds owned by farmers and thereby their greenhouse gases emissions.

Plate 6.3: Manure collection around watering point in the Sudan-Sahel zone. A. Watering point; B: Heap of manure collected and temporally stored under a shea tree. Source: author's Own compilation, 2023.

Manure and its management and ploughing are agricultural practices that induce carbon loss through its emission as carbon dioxide. To reduce emissions from manure (usually stored in solid form by the farmers), composting and its good management could be an efficient mitigation option (Novak and Fiorelli, 2010). For these authors, adding straw to the solid manure reduces $CH_4$ and $N_2O$ emissions from the manure heaps. Farm-scale total emissions were rather negatively and significantly correlated with the coverage of fodder needs (CoFN) ($-0.2 < r < -0.4$, $p < 0.05$). The higher percentage coverage of fodder needs was by farmers with the smallest herd size and the lower percentage was by farmers with larger herd size. Given that livestock greenhouse gas emission was the highest source of emission, explained why the emission was decreasing as the CoFN increased. The integration effectiveness (IE) was significantly negatively associated with emissions within the Sahel zone ($r = - 0.3$, $p < 0.05$). In this zone and similarly to the CoFN, the more the effectiveness of integration the smaller the herd size and lower the emissions. The integrated crop-livestock system should rely on herd size reduction (Novak and Fiorelli, 2010) but on more productive livestock species to reduce greenhouse emissions without adversely compromising productivity. Beyond the herd size reduction, the authors stressed the feeding strategies and genetic improvement towards low enteric emission breeds.

Nevertheless, in the context of Sub-Saharan Africa (SSA), if, for now, the genetic improvement might be challenging, alternative actions could additionally focus on: (i) diet improvement, (ii) good manure management; and (iii) the use of animal energy to support farm energy demand for both cultivation and transportation. The use of animal draft power is a way of reducing farmers' reliance solely on machinery (mainly through hiring) for ploughing and cultivation. Thus, reducing machinery utilisation in the farming system meant the reduction in the use of fossil fuel and consequently greenhouse gases emissions. This is in line with (Novak and Fiorelli, 2010), who defined fuel savings as a beneficial mitigation option.

The level of integration positively correlated with the total emission at the farm-scale but significantly only in the Sudan zone ($r = 0.4$, $p<0.05$), the Sahel zone ($r = 0.3$, $p<0.05$) and the global scale ($r = 0.2$, $p<0.05$) respectively. This means that the more the integration practices adopted, the more the emission from cropping (from chemical fertilizers), and livestock (enteric fermentation, manure management).

The total integration effort (TIE) positively and significantly correlated with the total emission in Sudan ($r = 0.3$) and Sudan-Sahel ($r = 0.2$) zones. Within these two zones, cropping intensification meant increased use of chemical fertilizer and more the emissions from agriculture. This was not the case in the Sahel, where chemical fertilizers were sparingly used. The coverage of crop financial needs (CoCFN) was positively associated with the total emission in the Sahel zone ($r = 0.5$, $p < 0.0.5$), while the coverage of livestock financial needs (CoLFN) was negatively associated with the emission in the Sudan zone ($r = - 0.3$, $p < 0.05$) and at global scale ($r = - 0.2$, $P < 0.05$). Thus, financial integration has different implications for emissions between Sahel and Sudan zones.

Emissions from cropping ($CO_{2ha}$) have a positive association with the coverage of manure needs (CoMN) in Sudan ($r = 0.2$, $P < 0.05$) and Sudan-Sahel ($r = 0.3$, $p < 0.05$) zones. In these zones, manure was used together with chemical fertilizers (NPK, Urea) in farm fertilisation and the bigger the farm size, the more chemical fertilizers were used and the higher the related emissions. These emissions showed, at a global scale, a negative association with the CoFN ($r = -0.4$, $p < 0.05$) and a positive association with the CoDPN ($r = 0.3$, $p < 0.05$). The CoFN decreased as one moved from Sudan-Sahel to the Sudan zone while farm sizes and their related emissions increased inversely moving from Sudan-Sahel to the Sudan zone. This could explain the negative association observed between CoFN and emission from cropping. On the contrary, the coverage of draft-power needs (CoDPN), farm size and their related emissions increased from Sudan-Sahel to the Sudan zone. This might be the cause of the positive observed association between CoDPN and the emission from cropping. It was observed at a global scale, a negative association of emissions from cropping with the integration effectiveness (IE) ($r = -0.2$, $p < 0.05$), the level of integration (LI) ($r = -0.1$, $P < 0.05$), the total integration effort (TIE) ($r = -0.3$, $p < 0.05$), and the financial integration ($r = -0.1$, $p < 0.05$). The emissions were rather positively associated in the Sudan zone with IE ($r = 0.2$, $P < 0.05$), LI ($r = 0.3$, $p < 0.05$) and TIE ($r = 0.2$, $p < 0.05$). Finally, these emissions are positively related to the coverage of crop financial needs (CoCFN) ($r = 0.5$, $p < 0.05$) and the financial integration in the Sudan-Sahel zone ($r = 0.3$, $p < 0.05$) (Table 6.11).

The emission per Tropical Livestock Unit ($TCO_{2TLU}$) is negatively associated at the global scale with the CoMN ($r = -0.1$, $p < 0.05$) and CoFN ($r = -0.1$, $p < 0.05$), respectively. This is positively associated with the level of integration in the Sudan-Sahel ($r = 0.2$, $p < 0.05$) and Sahel ($r = 0.2$, $p < 0.05$) zones, respectively. Moving from the Sahel to the Sudan zone, the CoMN decreased while the livestock emissions increased, thus explaining observed negative association between $TCO_{2TLU}$ and the CoMN. Globally, as CoFN decreased from Sahel and Sudan-Sahel to the Sudan zone, the $TCO_{2TLU}$ inversely increased across the zones. This also explains the negative association between the CoFN and the $TCO_{2TLU}$ .

Table 6.11: Interrelations between crop-livestock integration indicators and greenhouse gases across climatic zones of Burkina Faso.

| CLI indicators | Zones | CoMN | CoFN | CoDPN | IE | LI | TIE | CoCFN | CoLFN | FinCLI |
|---|---|---|---|---|---|---|---|---|---|---|
| $TCO_{2e}$ | Total | 0.00 | **-0.36*****| **0.39***** | 0.05 | **0.20***** | 0.08 | **0.13**** | **-0.17**** | 0.01 |
| | Dano | **0.25***** | **-0.23**** | **0.20*** | **0.37***** | **0.40***** | **0.27**** | 0.17 | **-0.27**** | 0.11 |
| | Dori | 0.08 | **-0.41***** | **-** | **-0.30***** | **0.27***** | 0.14 | **0.39***** | -0.04 | **0.31***** |
| | Niou | 0.09 | **-0.37***** | **0.37***** | 0.05 | 0.10 | **0.19**** | 0.06 | -0.11 | -0.00 |
| $CO_{2ha}$ | Total | -0.03 | **-0.41**** | **0.26***** | **-0.17**** | **-0.12*** | **-0.27**** | 0.05 | 0.10 | **-0.12*** |
| | Dano | **0.18*** | 0.02 | -0.01 | **0.16*** | **0.25**** | **0.16*** | 0.07 | -0.03 | -0.06 |
| | Dori | - | - | - | - | - | - | - | - | - |
| | Niou | **0.30***** | -0.01 | 0.08 | 0.08 | 0.14 | 0.03 | **0.45***** | -0.04 | **0.34***** |
| $TCO_{2eTLU}$ | Total | **-0.13**** | **-0.12**** | 0.06 | -0.08 | 0.06 | -0.04 | -0.04 | -0.04 | -0.05 |
| | Dano | 0.03 | -0.04 | -0.03 | -0.04 | 0.11 | 0.07 | -0.03 | -0.15 | 0.01 |
| | Dori | -0.12 | 0.14 | - | -0.05 | **0.20**** | -0.13 | -0.13 | -0.08 | -0.08 |
| | Niou | -0.13 | -0.06 | 0.00 | -0.03 | **0.17*** | 0.02 | -0.04 | 0.16 | -0.06 |

Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Legend: CoMN: Coverage of Manure Needs; CoFN: Coverage of Fodder Needs; CoDPN: Coverage of Draft Power Needs; IE: Integration Effectiveness; LI: Level of Integration; TIE: Total Integration Effort; CoCFN: Coverage of Crop Financial Needs; CoLFN: Coverage of Livestock Financial Needs; FinCLI: Financial Crop-livestock Integration. Source: author's Own computation, 2023.

#### 6.3.6.2 Crop-livestock integration and water productivity

Crop-livestock water productivity (Table 6.12) revealed a significant association with integration indicators. Livestock water productivity (LWP) was positively significantly interrelated with the coverage of manure needs (CoMN) in the Sahel ($r=0.4$, $p<0.05$) and Sudan-Sahel ($r=0.2$, $p < 0.05$) where the CoMN was comparatively higher. Effective coverage of farm manure needs could result in higher soil fertility and higher profit to buy supplementary feed (cotton cake usually) in the Sahel and Sudan-Sahel to boost livestock productivity (milk and meat). Inversely, LWP significantly negatively correlated with the coverage of fodder needs (CoFN) across all the climatic zones. The coverage of draft-power needs (CoDPN) positively correlated with LWP in the Sudan-Sahel, where cropping relies largely on animal energy (draft oxen representing 23.8 % of the cattle owned by farmers in the zone). Thus, the increased coverage of draft power is associated with a comparatively bigger size of oxen and their higher carcass weight contribution to LWP. In the Sudan zone the association was not significant because the productivity in this zone relies not that much on oxen (representing 33.4 % of the cattle owned by farmers in the Sudan zone (Appendix 11)) but rather on an important number of other livestock categories (representing 66.6 % of the cattle owned by farmers in the zone (Appendix 11)) bred by farmers in the zone. Indeed, cattle that contribute more to livestock water productivity had the highest herd size (5.2±5.6 TLU) in the Sudan zone. This is almost double that in Sudan-Sahel (2.4±2.4 TLU) and Sahel (2.8±2.7 TLU) zones. Both in the Sahel zone and at a global scale, the coverage of crop financial needs (CoCFN) positively and significantly influenced LWP ($P < 0.05$). A successful cropping results in more available crop residues for livestock grazing within such a harsh environment where livestock feeding remained a challenging issue to productivity.

Both financial (CWP-F) and physical crop water productivity (CWP-P), and total water productivity (TWP) positively and significantly correlated ($0.2 < r < 0.4$, $P < 0.05$) with the CoMN across the climatic zones. The more the coverage of croplands fertility needs, the more their productivity. Besides the uses of chemical fertilizers in Sub-Saharan Africa, manure also contributes significantly to soil fertility maintenance. Thus, the integrated crop-livestock system in the region significantly underpins farm productivity, including water productivity. This corroborated previous findings on the role of mixed farming to potentially achieving high land productivity, ensuring good incomes while conserving natural resources (water, air, soils….) and produce valuable ecosystem services (Novak and Fiorelli, 2010). In this regard, CLI can contribute to increasing the resilience of the agricultural sector against climatic and economic constraints (Novak and Fiorelli, 2010).

The CoFN was significantly but negatively correlated ($r = - 0.2$, $P < 0.05$) with the total water productivity (TWP) in Sudan and Sahel zones. Indeed, as the CoFN decreased from the Sudan-Sahel and Sahel zones to the Sudan zone, water productivity was found inversely increasing. The Total Water Productivity (TWP) also significantly and positively correlated with the CoDPN at a global scale and within the Sudan-Sahel zone. This gives an idea of the role played by livestock draft power in water productivity in a harsh environment usually characterized by low soil fertility. The integration effectiveness (IE) also positively and significantly correlated ($0.2 < r < 0.3$, $P < 0.05$) with physical and financial crop water productivity (CWP-P, CWP-F) and the TWP across all the zones. This means that the more the farming system performs an effective coverage of its needs in fodder, manure and draft power, the better the performance of this system to produce from a lower amount of water depleted. It is in this perspective that Wells et al. (2000) qualified the mixed farming such as CLI to be a way of efficient uses of natural resources including water resources. The global level of integration was negatively associated ($r = -0.2$, $P < 0.05$) with water productivity in the Sahel and positively in Sudan ($0.2 < r < 0.3$, $P < 0.05$). The total integration effort (TIE) revealed a positive and significant association with water productivity in Sahel and Sudan ($r = 0.2$, $P < 0.05$), unlike the Sudan-Sahel zone. It can be concluded that the positive association implies that farmers' efforts to integrate crops and livestock have improved water use efficiency in the Sahel and Sudan zones. In the transition zone (Sudan-Sahel), even though water productivity was positively associated with the TIE, this was not significant. Farmers' efforts in this transition zone to mobilise manure for soil fertilisation purposes might not have sufficiently improved soil water holding capacity to ensure good water productivity.

The coverage of crop financial needs (CoCFN) and financial integration was positively and significantly associated with water productivity in the Sahel and Sudan-Sahel ($0.2< r <0.4$, $P < 0.05$). Effective financial support for CLI is essential for good production performance. The support included the hiring of the workforce, and purchase of manure and other agricultural inputs (seeds, pesticides, NPK, Urea...). At a global scale the financial integration is significantly positively associated with total water productivity (TWP) as one moves from the Sahel to the Sudan-Sahel and Sudan zones.

The positive association of crop-livestock integration with soil nutrients can explain the interrelation between productivity and integration. Overall, the weak level of integration indicated in chapter 5 could not have been enough to support both soil fertility and water productivity. That is why farmers' soil fertility maintenance strategies in the Sudan and Sudan-Sahel zones mainly rely on the use of chemical fertilizers (NPK, Urea).

The increase in farm productivity because of CLI gives insights into the potential role it can play in this mixed cropping system in building both resilient farmers and farming systems across climatic zones of Burkina Faso.

Table 6.12: Interrelations between crop-livestock integration indicators and water productivity across climatic zones of Burkina Faso

| CLI indicators | Zones | CoMN | CoFN | CoDPN | IE | LI | TIE | CoCFN | CoLFN | FinCLI |
|---|---|---|---|---|---|---|---|---|---|---|
| LWP | Global | -0.03 | **-0.31**$^{***}$ | **0.30**$^{***}$ | 0.05 | -0.07 | 0.02 | **0.19**$^{***}$ | **-0.17**$^{*}$ | 0.06 |
| | Dano | 0.04 | **-0.40**$^{***}$ | 0.11 | 0.14 | -0.07 | 0.06 | 0.15 | -0.18 | 0.07 |
| | Dori | **0.37**$^{***}$ | **-0.33**$^{***}$ | **-** | 0.07 | -0.04 | 0.14 | **0.50**$^{***}$ | -0.24 | **0.36**$^{***}$ |
| | Niou | **0.21**$^{**}$ | **-0.26**$^{***}$ | **0.28**$^{***}$ | 0.09 | 0.08 | -0.02 | 0.09 | **-0.22**$^{*}$ | 0.05 |
| CWP-P | Global | **0.22**$^{***}$ | **-0.12**$^{**}$ | **0.18**$^{**}$ | **0.10**$^{*}$ | -0.06 | 0.01 | **0.16**$^{***}$ | -0.04 | 0.04 |
| | Dano | **0.23**$^{***}$ | -0.01 | 0.02 | **0.20**$^{**}$ | **0.21**$^{**}$ | **0.22**$^{**}$ | 0.15 | -0.15 | 0.05 |
| | Dori | **0.35**$^{***}$ | -0.13$^{.}$ | - | **0.20**$^{**}$ | **-0.19**$^{**}$ | **0.20**$^{**}$ | **0.21**$^{*}$ | -0.15 | 0.16 |
| | Niou | **0.44**$^{***}$ | 0.14$^{.}$ | 0.11 | **0.20**$^{**}$ | -0.05 | 0.01 | **0.30**$^{***}$ | 0.02 | **0.21**$^{**}$ |
| CWP-F | Global | **0.29**$^{***}$ | -0.05 | 0.11 | **0.12**$^{**}$ | -0.03 | 0.01 | **0.13**$^{**}$ | -0.04 | 0.06 |
| | Dano | **0.25**$^{***}$ | 0.004 | 0.04 | **0.20**$^{**}$ | **0.18**$^{*}$ | **0.18**$^{*}$ | 0.14 | -0.15 | 0.01 |
| | Dori | **0.37**$^{***}$ | -0.14 | - | **0.22**$^{**}$ | **-0.18**$^{*}$ | **0.16**$^{*}$ | **0.25**$^{**}$ | -0.18 | **0.21**$^{*}$ |
| | Niou | **0.30**$^{***}$ | 0.12 | 0.05 | 0.12 | -0.02 | 0.01 | **0.22**$^{**}$ | 0.004 | **0.19**$^{*}$ |
| TWP | Global | **0.24**$^{***}$ | **-0.22**$^{***}$ | **0.30**$^{***}$ | **0.15**$^{***}$ | 0.04 | 0.06 | **0.18**$^{***}$ | **-0.13**$^{*}$ | **0.10**$^{*}$ |
| | Dano | **0.20**$^{***}$ | **-0.20**$^{*}$ | 0.16 | **0.27**$^{***}$ | **0.28**$^{***}$ | **0.21**$^{**}$ | 0.10 | **-0.15**$^{.}$ | 0.06 |
| | Dori | **0.42**$^{***}$ | **-0.19**$^{*}$ | - | **0.18**$^{*}$ | -0.10 | **0.20**$^{**}$ | **0.41**$^{***}$ | -0.23 | **0.29**$^{***}$ |
| | Niou | **0.37**$^{***}$ | -0.11 | **0.27**$^{***}$ | **0.18**$^{*}$ | 0.01 | 0.05 | **0.22**$^{**}$ | -0.15 | **0.15**$^{*}$ |

Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Legend: CoMN: Coverage of Manure Needs; CoFN: Coverage of Fodder Needs; CoDPN: Coverage of Draft Power Needs; IE: Integration Effectiveness; LI: Level of Integration; TIE: Total Integration Effort; CoCFN: Coverage of Crop Financial Needs; CoLFN: Coverage of Livestock Financial Needs; FinCLI: Financial Crop-livestock Integration. Source: author's Own computation, 2023.

#### 6.3.6.3 Crop-livestock integration and biomass carbon sequestration and tree diversity

At a global scale, the coverage of manure needs (CoMN) and the fodder needs (CoFN) are negatively associated (-0.2 < r < -0.4, P<0.05) with tree carbon stock (Aboveground stock (ABC), Belowground stock (BGC), Total carbon stock ($Tot_{seq}$)). Usually, larger farm sizes are associated with higher carbon stocks but lower coverage of manure and fodder needs. This could explain the observed negative association of carbon stock with the CoMN and CoFN. In the Sudan zone, carbon stock potential increases accordingly to the level of crop-livestock integration (r < 0.3, P<0.05). In the Sahel zone, the coverage of crop financial needs (CoCFN) is negatively and significantly associated with carbon stock (-0.3< r < -0.4, P<0.05). This means the more the coverage of crop financial needs, the less carbon storage potential of the farming system in the Sahel zone. This negative interrelation might be explained by the fact that farms benefiting from high financial inputs to support crop production might keep comparatively fewer trees on fields than those with low financial inputs. The focus was more on the input's cost-effectiveness than on tree conservation.

Tree species richness and diversity globally were significantly and positively associated with the coverage of manure needs (CoMN). Manure application could contribute to the improvement of farm biodiversity. Indeed, organic manure is generally rich in seeds which are yearly disseminated throughout the cultivated land with the spreading of manure. The diversity indices (S and H) were also significantly and positively associated with the CoFN and were found to decrease from the Sudan-

Sahel and Sahel zones to the Sudan zone. Globally the CoDPN did not significantly associate with the species richness and diversity (Table 6.13). This could also explain the overall insignificant association with the integration effectiveness, nevertheless, at the global scale, species richness (S) is significantly and positively associated with the integration effectiveness, while the level of integration negatively interrelates with species richness (S) and diversity (H, D) only within the Sahel zone ($P<0.05$).

More carbon storage in the field implies more carbon removal from the atmosphere. This means that the positive interrelation of carbon storage with the integration indicators gives insights into the potential role played by CLI in climate change mitigation and building resilient farming systems. Likewise, the positive association of the integration indicators (CoMM, CoFN, IE) with diversity indices indicates the potential role of CLI in biodiversity conservation for sustainable farming in Burkina Faso.

Table 6.13: Interrelations between crop-livestock integration indicators and biomass carbon and tree diversity across climatic zones of Burkina Faso

| CLI indicators | Zones | CoMN | CoFN | CoDPN | IE | LI | TIE | CoCFN | CoLFN | FinCLI |
|---|---|---|---|---|---|---|---|---|---|---|
| AGC | Global | **-0.28**$^{**}$ | **-0.16**$^{*}$ | 0.12 | 0.02 | 0.12 | -0.02 | 0.04 | -0.06 | -0.04 |
| | Dano | 0.11 | -0.19 | 0.12 | 0.12 | **0.26**$^{*}$ | -0.03 | -0.06 | -0.03 | -0.06 |
| | Dori | -0.15 | -0.09 | - | -0.18 | 0.15 | -0.17 | **-0.34**$^{*}$ | 0.36 | - 0.20 |
| | Niou | -0.08 | -0.14 | -0.06 | -0.03 | 0.11 | -0.08 | 0.04 | 0.01 | 0.02 |
| BGC | Global | **-0.29**$^{**}$ | **-0.17**$^{*}$ | 0.13 | 0.02 | 0.12 | -0.03 | 0.04 | -0.05 | -0.04 |
| | Dano | 0.12 | -0.19 | 0.13 | 0.12 | **0.26**$^{*}$ | -0.02 | -0.05 | -0.03 | -0.06 |
| | Dori | -0.15 | -0.09 | - | -0.18 | 0.14 | -0.18 | **-0.35**$^{*}$ | 0.35 | -0.20 |
| | Niou | -0.08 | -0.14 | -0.06 | -0.02 | 0.10 | -0.08 | 0.04 | 0.02 | 0.01 |
| $Tot_{Seq}$ | Global | **-0.28**$^{**}$ | **-0.16**$^{*}$ | 0.13 | 0.02 | 0.12 | -0.02 | 0.04 | -0.06 | -0.04 |
| | Dano | 0.11 | -0.19 | 0.12 | 0.12 | **0.26**$^{*}$ | -0.03 | -0.05 | -0.03 | -0.06 |
| | Dori | -0.15 | -0.09 | - | -0.18 | 0.14 | -0.17 | **-0.35**$^{*}$ | 0.36 | -0.19 |
| | Niou | -0.08 | -0.14 | -0.06 | -0.03 | 0.11 | -0.08 | 0.04 | 0.02 | 0.02 |
| S | Global | **0.16**$^{*}$ | **0.22**$^{**}$ | -0.04 | **0.17**$^{*}$ | 0.09 | **0.23**$^{**}$ | **-0.18**$^{*}$ | -0.05 | **0.23**$^{**}$ |
| | Dano | -0.02 | -0.30 | 0.29 | 0.16 | 0.21 | 0.03 | -0.02 | -0.05 | -0.04 |
| | Dori | 0.14 | -0.09 | - | -0.02 | **-0.40**$^{*}$ | -0.15 | 0.30 | -0.13 | 0.29 |
| | Niou | 0.25 | 0.19 | -0.13 | 0.05 | 0.02 | 0.16 | 0.09 | 0.06 | 0.09 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| H | Global | **0.27**** | **0.19*** | -0.05 | 0.09 | 0.05 | 0.04 | 0.08 | 0.07 | 0.15 |
| | Dano | 0.01 | -0.37 | 0.16 | 0.03 | 0.15 | -0.03 | 0.05 | 0.09 | -0.05 |
| | Dori | 0.10 | -0.02 | - | 0.10 | **-0.39*** | -0.19 | **0.38*** | -0.24 | 0.29 |
| | Niou | 0.24 | 0.18 | 0.01 | 0.01 | 0.00 | -0.08 | -0.06 | 0.19 | 0.02 |
| D | Global | **0.26**** | 0.15 | -0.05 | 0.05 | 0.06 | -0.02 | 0.03 | 0.12 | 0.09 |
| | Dano | -0.01 | -0.37 | 0.11 | -0.00 | 0.12 | -0.04 | 0.05 | 0.11 | -0.08 |
| | Dori | 0.07 | 0.05 | - | 0.16 | **-0.31*** | -0.18 | 0.31 | -0.25 | 0.21 |
| | Niou | 0.18 | 0.11 | 0.02 | -0.04 | -0.01 | -0.16 | -0.08 | 0.22 | -0.01 |
| Tree density | Global | -0.01 | 0.01 | -0.00 | 0.07 | 0.10 | 0.10 | 0.13 | -0.22 | 0.08 |
| | Dano | 0.00 | -0.18 | 0.11 | 0.13 | 0.15 | -0.05 | 0.11 | -0.26 | -0.12 |
| | Dori | 0.09 | -0.10 | - | -0.05 | 0.06 | 0.10 | 0.08 | 0.21 | 0.24 |
| | Niou | 0.08 | 0.01 | -0.15 | -0.01 | 0.03 | 0.09 | 0.07 | -0.16 | 0.02 |

Signif. Codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1. Legend: CoMN: Coverage of Manure Needs; CoFN: Coverage of Fodder Needs; CoDPN: Coverage of Draft Power Needs; IE: Integration Effectiveness; LI: Level of Integration; TIE: Total Integration Effort; CoCFN: Coverage of Crop Financial Needs; CoLFN: Coverage of Livestock Financial Needs; FinCLI: Financial Crop-livestock Integration. Source: author’s Own computation, 2023.

#### 6.3.6.4 Crop-livestock integration and soils carbon and properties

Some crop-livestock integration indicators showed a significant association with soil organic carbon and properties (Table 6.14). Indeed, the pH was significantly associated with the coverage of livestock financial needs (CoLFN) ($r = 0.5$, $p < 0.05$) but only in the Sudan-Sahel zone. Soil fertility in this zone, was not influenced by manure application, crop-residues exportations from fields and ploughing. Nevertheless, within the zone, the pH seems rather more controlled by the coverage of crop financial needs including the purchase and uses of chemical fertilizers.

Soil nitrogen concentration was positively correlated with the coverage of manure needs (CoMN) in the Sudan zone ($r = 0.4$, $p <0.05$). Soil phosphorus positively and significantly correlated with the financial integration (FinCLI) in the Sudan-Sahel zone ($r = 0.3$, $p <0.05$) while the potassium significantly correlated with both the coverage of crop financial needs (CoCFN) ($r = 0.3$, $p <0.05$) and livestock financial needs (CoLFN) ($0.3 < r < 0.6$, $p <0.05$) within the Sudan and Sudan-Sahel zones respectively. It appears, therefore, that soil nitrogen content in the Sudan zone is more controlled by manure application in line with the correlation observed between manure nitrogen content ($N_{dung}$) and soil nitrogen content ($N_{soil}$) (Section 6.3.4.3, Table 6.9). This correlation was higher ($r=0.17$, $P<0.05$) than it has been ($r=0.16$, $P<0.05$) between soil nitrogen ($N_{soil}$) content and chemical nitrogen inputs ($N_{ch}$). On the contrary, the soil phosphorus ($P_{soil}$) and soil potassium ($K_{soil}$) rather rely more on the financial integration indicators (i.e. more on chemical inputs) than on the physical integration indicators (manure inputs, fodder exportation, ploughing). This was also corroborated by the observed correlation in Section 6.3.4.3 (Table 6.9) indicating that soil phosphorus ($P_{soil}$) content was more controlled by chemical phosphorus inputs ($P_{ch}$) than manure (r= 0.21 vs a r=0.17 for $P_{dung}$) (Table 6.9. Similarly, this was in line with the observed situation indicating that soil potassium ($K_{soil}$) content relies more on chemical fertilizer than on manure application (r=0.39 vs r=0.36 for $K_{dung}$) (Table 6.9). Nevertheless, the positive association between soils K and P and manure K and P, respectively gives room to act for soil fertility reclamation through effective coverage of farm manure needs. This means more effort and it is possible to increase manure production in sufficient amounts for fertilisation purposes across climatic zones. Indeed, as reported by Peyraud et al. (2014), a herd of 200 ewes produces 710 kg of N, 770 kg of P and 1050 kg of K, sufficient to fertilize up to 15 ha each year, thus reducing outlay on chemical fertilizers. In the context of Burkina Faso and SSA in general, manure mobilisation effort could rely on much fewer livestock, given generally smaller farm size characteristics within the region. For a typical farmer cultivating on average three (3) hectares, a herd size of 40 sheep is enough fertilize its three (3) hectares successfully.

Soil bulk density was positively and significantly associated with the coverage of manure in the Sudan zone ($r = 0.5$, $P < 0.05$) and with draft power needs ($r = 0.2$, $P < 0.05$) at a global scale. This means that manure application and soil ploughing improve soil bulk density.

The percentage of soil carbon significantly and positively correlated with the coverage of manure needs (CoMN) ($r = 0.4$, $p < 0.05$), the coverage of crop financial needs (CoCFN) ($r = 0.3$, $p < 0.05$) and the financial integration (FinCLI) ($r = 0.3$, $p < 0.05$) in the Sudan zone while significantly and negatively correlated with CoFN ($r = -0.4$, $p < 0.05$) and the TIE ($r = -0.2$, $p < 0.05$) at a global scale. Finally, the SOC was associated significantly and positively with the CoMN ($r = 0.4$, $p < 0.05$) and FinCLI ($r = 0.3$, $p < 0.05$) in the Sudan zone. At the global scale, the SOC was significantly and negatively associated with CoFN ($r = -0.4$, $p < 0.05$) and TIE ($r = -0.2$, $p < 0.05$) but positively with CoDPN ($r = 0.2$, $p < 0.05$). These results suggest that soil carbon storage could be significantly improved through manure application, and the ploughing intensity (turnover of organic matter into the soil). This aligned with the assertion that manure application increases long-term SOC (Peyraud et al., 2014). In addition, the financial integration through the purchase and use of chemical fertilizers also improve soil carbon storage. Indeed, as was observed in the Section 6.3.4, Table 6.10; chemical Nitrogen ($r=0.29$, $p<0.05$); Potassium ($r=0.20$, $p<0.05$) and Phosphorus ($r=0.20$, $p<0.05$) significantly associated with and could have improved the soil carbon percentage. On the contrary, the coverage of farm fodder needs (CoFN) is negatively associated with the soils carbon stock and nutrients. Indeed, these nutrients could be depleted along with crop-residues exportation from the field for livestock feeding, thus, adversely impacting nutrient recycling and their returns to the soil for fertility maintenance. Farmers should ensure the return of exported nutrients (through the crop-residues collection) back to fields along with adequate livestock manure and compost inputs into the cultivated lands. They could engage in a nutrient recycling loop between soil, herd and crops/tree biomass, essential for the system sustainability and reducing its reliance on inorganic fertilizers. This aligned with Peyraud et al. (2014), who indicated that mixed-farming systems such as CLI, increased the possibilities of better recycling of nutrients within systems, limiting recourse to the purchase of increasingly expensive inputs and safeguarding the biodiversity of agricultural ecosystems. This contributes to building more resilient farmers and farming systems to face the adverse impacts of climate change including soil fertility decline and low land productivity.

Table 6.14: Interrelations between CLI indicators and soil nutrients and carbon sequestration across climatic zones of Burkina Faso

| CLI indicators | Zones | CoMN | CoFN | CoDPN | IE | LI | TIE | CoCFN | CoLFN | FinCLI |
|---|---|---|---|---|---|---|---|---|---|---|
| pH | Global | 0.00 | -0.08 | -0.02 | -0.02 | -0.15 | -0.01 | 0.08 | 0.22 | 0.09 |
| | Dano | -001 | -0.03 | -0.05 | -0.14 | -0.21 | -0.02 | 0.00 | 0.00 | 0.03 |
| | Niou | 0.03 | -0.07 | 0.01 | 0.09 | -0.11 | 0.03 | 0.16 | **0.53**** | 0.16 |
| N | Global | 0.11 | -0.13 | 0.10 | 0.02 | 0.10 | -0.05 | 0.13 | -0.04 | 0.02 |
| | Dano | **0.38*** | -0.21 | 0.10 | 0.13 | 0.18 | 0.05 | 0.25 | -006 | 0.15 |
| | Niou | 0.06 | 0.12 | -0.19 | -0.11 | 0.01 | 0.00 | 0.02 | -0.03 | 0.07 |
| P | Global | -0.03 | **-0.28**** | **0.24*** | -0.10 | -0.04 | -0.11 | -0.08 | 0.08 | -0.08 |
| | Dano | 0.18 | -0.05 | 0.14 | -0.04 | 0.07 | 0.03 | -0.06 | 0.05 | 0.01 |
| | Niou | 0.20 | 0.08 | -0.07 | 0.06 | -0.13 | 0.09 | 0.277 | 0.29 | **0.33*** |
| K | Global | 0.03 | -0.01 | 0.01 | 0.11 | 0.10 | 0.02 | 0.16 | **0.28*** | 0.15 |
| | Dano | 0.20 | 0.04 | 0.03 | 0.10 | 0.16 | 0.07 | **0.33*** | 0.21 | 0.40* |
| | Niou | -0.15 | 0.01 | -0.03 | 0.10 | -0.17 | -0.11 | -0.01 | **0.55*** | 0.03 |
| Bulk Density | Global | 0.12 | -0.12 | **0.21*** | 0.03 | -0.00 | -0.00 | 0.05 | 0.09 | -0.01 |
| | Dano | **0.46*** | -011 | 0.28 | 0.24 | 0.08 | 0.03 | 0.06 | 0.12 | 0.13 |
| | Niou | 0.09 | 0.05 | -0.03 | -008 | 0.05 | 0.18 | 0.12 | 0.01 | 0.07 |
| C (%) | Global | -0.09 | **-0.41**** | **0.20.** | -0.15 | -0.06 | **-0.20*** | 0.09 | 0.07 | -0.11 |
| | Dano | **0.28*** | -0.25 | -0.02 | -0.01 | 0.14 | 0.04 | **0.32*** | 0.11 | **0.28*** |
| | Niou | -0.05 | -0.09 | 0.09 | -0.01 | 0.18 | 0.17 | 0.16 | -0.32 | 0.13 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SOC | Global | -0.04 | **-0.39**** | **0.23*** | -0.12 | -0.05 | **-0.19*** | 0.08 | 0.11 | -0.09 |
| | Dano | **0.38*** | -0.23 | 0.04 | 0.05 | 0.14 | 0.02 | 0.29 | 0.17 | **0.29*** |
| | Niou | 0.01 | -0.02 | 0.07 | -0.04 | 0.17 | 0.24 | 0.20 | -0.28 | 0.15 |

Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Legend: CoMN: Coverage of Manure Needs; CoFN: Coverage of Fodder Needs; CoDPN: Coverage of Draft Power Needs; IE: Integration Effectiveness; LI: Level of Integration; TIE: Total Integration Effort; CoCFN: Coverage of Crop Financial Needs; CoLFN: Coverage of Livestock Financial Needs; FinCLI: Financial Crop-livestock Integration. Source: author's Own computation, 2023.

From above, the integrated crop-livestock system could be seen as an important alternative of climate change mitigation and a strategy for more resilient farming systems in Burkina Faso. Nevertheless, one should be interested in the best way of integrating crop and livestock modules for better economic and ecological performances of the system.

### 6.3.7 Best combination of mixed crop-livestock system

From the Principal component Analysis (PCA) three principal components were derived (Table 6.15). The first component consisted of the dimension of productivity and related greenhouse gas emission; the second dimension identified itself as that of carbon sequestration and the last dimension as that of integration effectiveness.

Table 6.15: Results of Principal Component Analysis: factor loadings

| Name of Variables | Components | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Integration effectiveness | 0.20 | 0.38 | **0.89** |
| Carbon dioxide emission ($TCO_{2eq}$) | **0.70** | -0.34 | 0.04 |
| Aboveground carbon stock ($Tot_{seq}$) | 0.37 | **0.73** | -0.43 |
| Crop water productivity (CWP) | **0.70** | -0.45 | -0.01 |
| Livestock Water Productivity (LWP) | **0.73** | 0.28 | -0.05 |
| Eigenvalues | 2.2 | 1.1 | 0.8 |
| Variance (%) | 41.7 | 26.4 | 17.1 |
| Cumulative (%) | 41.7 | 68.1 | 85.1 |

N.B. Bold numbers refer to loadings higher than 0.5. Source: author's Own computation, 2023.

From the subsequent Hierarchical Ascendant Clustering, four clusters were identified and characterised as follows (Figure 6.14 ):

The **cluster 1** identified as less resilient and low sustainable farming system, comprises farming households characterised by low sequestration potential, low productivity and weak greenhouse gas emissions.

The **cluster 2** identified as sustainable farming households with less resilient farmers. It is made of individual farmers characterized by high sequestration potential, low productivity and low greenhouse gas emissions.

The **cluster 3** identified itself as low sustainable farming households with more resilient farmers. This cluster is made of individual farmers that revealed a low sequestration potential but a high productivity and related greenhouse gas emissions.

The **cluster 4** distinguished itself as a tree-based system with the best combination of crop-livestock activities (Figure 6.14) that contribute to sustainable productions for more resilient farmers and farming systems. Indeed, this cluster is the one that conjointly performed best in terms of water productivity and the mitigation potential of emitted greenhouse gases during the production processes of both livestock and crop products. It is the one under which good enough water productivity was obtained while, at the same time, a good sequestration potential was ensured to counterbalance to some extent, the high emissions associated with the related individual farming households (Figure 6.14). This cluster of farmers is structurally characterized by an average farm size, herd size, oxen and tree density of 4.3±3.3 ha, 6.0±3.1 TLU, 2±1 oxen and 33.0±23.1 trees/ha respectively (Table 6.16). The functional characteristics of farming households of this cluster indicated plant and soil carbon storage potential of 11.3±7.6 Mg/ha and 18.0±10.6 Mg/ha, respectively, corresponding to 178.2 ± 119.8 Mg $CO_2$e and 283.8 ± 167.1 Mg $CO_2$e sequestrated by plant and soil respectively given an average crop area of 4.3±3.3 ha. Greenhouse gases emission potential was 12.0±6.3 Mg $CO_2$ equivalents. Soil nutrient contents were 1.0 ±0.4 % (carbon), 0.1 ± 0.0 % (nitrogen), 3.0 ± 1.0 mg/kg (phosphorus) and 59.4 ± 24.3 mg/kg (potassium). This Cluster also outperformed in terms of crop-livestock integration effectiveness (74.9±59.6 %), suggesting that individual farmers that performed higher crop-livestock integration distinguished themselves with a more resilient farming system.

Table 6.16: Structural and functional characteristics of crop-livestock integration across climatic zones of Burkina Faso

| Cluster | IE (%) | Farm size (ha) | TLU (n) | Oxen (n) | CWP (kg/m$^3$) | LWP (US$/m$^3$) | T.D (trees/ha) | GHG ($CO_{2e}$) | Tree Seq. (Mg/ha) | Soil C (%) | SOC (Mg/ha) | Soil N (%) | Soil P (mg/kg) | Soil K (mg/kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 51.5±32.7 | 4.7±2.7 | 3.6±2.6 | 1.4±0.5 | 0.3±0.2 | 0.1±0.0 | 17.2±10.2 | 6.9±5.0 | 4.7±2.2 | 0.9±0.3 | 14.0±3.2 | 0.08±0.02 | 2.8±1.1 | 75.5±33.3 |
| 2 | 42.8±28.5 | 5.5±2.7 | 4.0±1.9 | 1.1±1.1 | 0.3±0.1 | 0.1±0.1 | 26.9±13.1 | 7.9±4.4 | 13.1±4.4 | 1.0±0.4 | 15.9±7.2 | 0.08±0.03 | 3.6±4.5 | 74.9±36.9 |
| 3 | 60.7±43.7 | 8.5±8.4 | 14.3±8.1 | 2.7±1.5 | 0.6±0.3 | 0.1±0.1 | 26.7±13.6 | 29.0±15.3 | 8.2±3.5 | 1.1±0.4 | 14.4±5.3 | 0.09±0.04 | 3.5±1.8 | 72.9±62.6 |
| 4 | 74.9±59.6 | 4.3±3.3 | 6.0±3.1 | 2.0±1.0 | 0.4±0.3 | 0.4±0.1 | 33.0±23.1 | 12.0±6.3 | 11.3±7.6 | 1.0±0.4 | 18.0±10.6 | 0.09±0.02 | 3.0±1.0 | 59.4±24.3 |

Legend : IE: Integration Effectiveness; T.D is tree density; CWP: Crop-Water productivity; LWP: Livestock Water Productivity; Tree Seq.: Tree sequestration; SOC: Soil Carbon Stock. Values: mean±sd. Source: author’s Own computation, 2023.

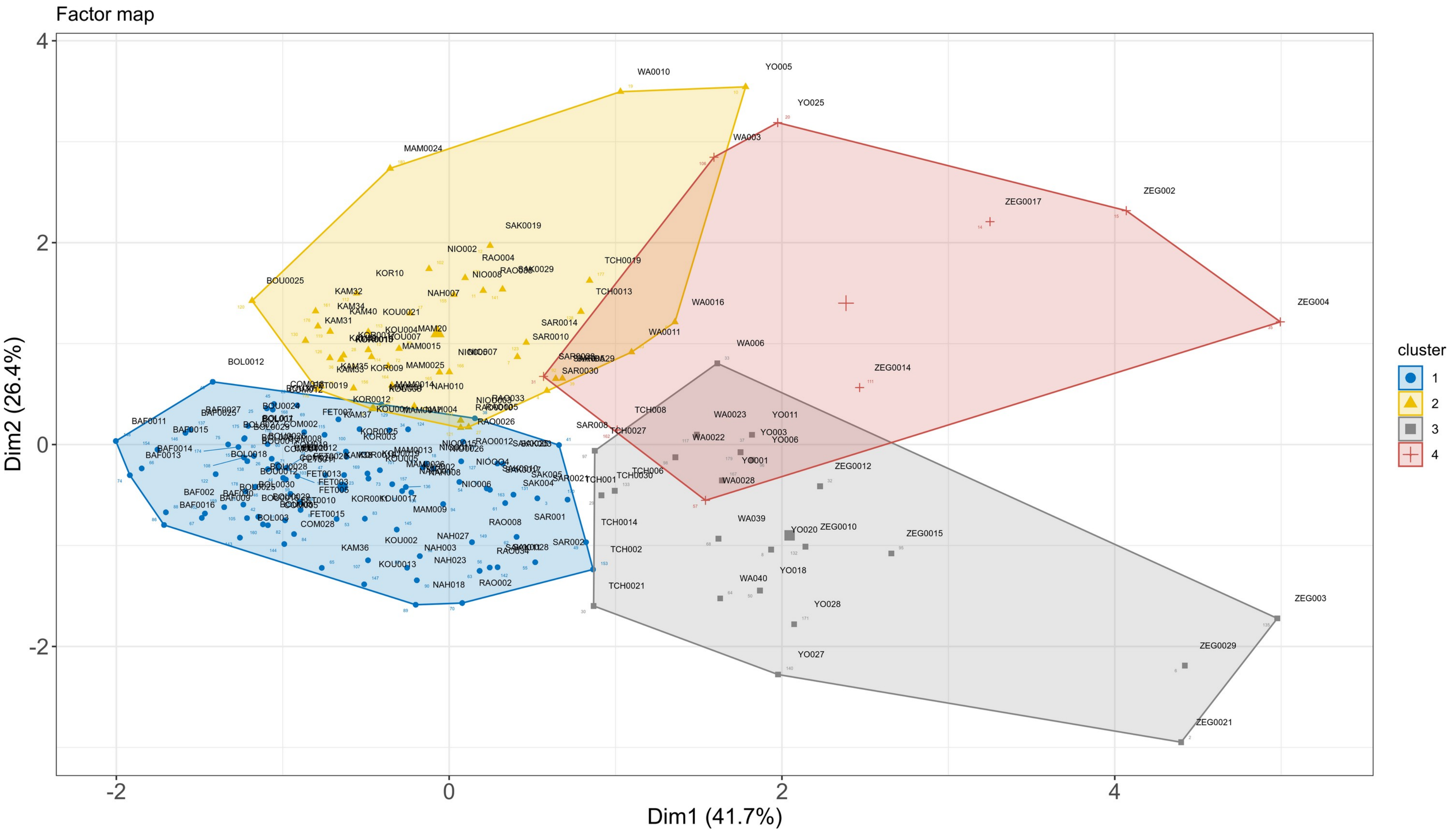


Figure 6.14: Cluster plot showing the four clusters of farmers' households (outcome of the hierarchical cluster analysis). Component 1 explained 41.7 % of the variables and summarised the emission and productivity variables. Component 2 explained 26.4 % of the variables and identified itself to the carbon sequestration variables. Source: author's Own computation, 2023.

### 6.4 Conclusion

Findings from the study indicated that crop-livestock integration (CLI) positively interrelates with water productivity, meaning that this mixed farming could improve farmers' livelihood and build their resilience to the adverse impact of climate change. Likewise, CLI positively correlated with soil nutrients including carbon, nitrogen, phosphorus and potassium among which the manure inputs more controlled carbon and nitrogen. On the contrary, soil phosphorus and potassium contents were rather more controlled by chemical inputs (NPK and Urea). Nevertheless, they significantly positively correlated with manure inputs attesting to the role played by CLI in soil fertility maintenance which could potentially be improved through much more effective integration beyond the observed effectiveness across climatic zones (35.6 %, 44.9 % and 65.9 % within Sudan, Sahel and Sudan-Sahel zones respectively). In addition, CLI is associated with the maintenance of tree species on the farm, mainly through seed spreading over the field along with manure applications. Trees on farms play both the role of carbon storage and biodiversity conservation, besides other ecosystem services they could provide to the agro-systems.

Nevertheless, CLI is also associated with a high amounts of greenhouse gases emissions ($CO_2$, $N_2O$ and $CH_4$ etc.) as a result of cropping and livestock rearing activities that are fortunately balanced to some extent by the sequestration potential of the system through soil and plants reservoirs. In a nutshell, besides a productive performance it ensures, CLI could result in limiting the purchase of increasingly expensive agricultural inputs, safeguarding the biodiversity of agricultural ecosystems, and enhancing the removal of carbon dioxide from the atmosphere. This could be achieved by choosing an adequate farm size, herd size, number of oxen, and a good tree density to keep on the farm. CLI is a potential way of building more resilient farmers and farming systems to face climate change and its adverse impacts across climatic zones of Burkina Faso.

# CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

## 7.1 Conclusion

In line with the specific objectives set for the study, the following conclusions can be drawn:

(i) There is evidence of climate change across Burkina Faso's climatic zones whatever the analysis scale used (annual, seasonal and decadal). The changes were more pronounced in temperature and the related extreme indices than in rainfall and related wet indices. Furthermore, the hot indices were found to evolve much faster than their counterpart cold indices. Moreover, a re-wetting trend globally characterized the Sudan-Sahel and Sahel zone ascertaining the re-greening thesis of the Sahel from previous literature.

(ii) Despite some positive influences across zones, climate trends generally adversely affected crop farming (crop failure) and livestock rearing (diseases resurgence) across zones. Farmers' livelihoods are therefore undergoing an unprecedented threat that is increasing their vulnerability.

(iii) The conception of crop-livestock integration (CLI) indicators contributes to filling a gap in integration assessment tools. Generally, CLI was found to be underperforming across all climatic zones and could be potentially improved through more efforts (educational, financial, technical, conceptual etc.) toward the effective and efficient integration of crop and livestock modules in the context of climate change.

(iv) Crop-livestock integration has the potential to significantly improve both crop and livestock production and much more their water productivity. This is with respect to CLI’s positive impact on soil fertility maintenance and its water-holding capacity. CLI is also positively associated with soil carbon storage and as a tree-based system, contributing, therefore to the mitigation process. CLI, through animal manure inputs, supports tree regeneration as seeds in the faecal matter deposited by the ruminants are spread on the field. The integrated crop-livestock system promotes tree biodiversity conservation and carbon sequestration (in soils and plants) to counterbalance the system emissions through a good combination of crop and livestock modules. Overall, such mixed farming system offers an opportunity for sustainability and more resilient farming systems.

## 7.2 Recommendations

### 7.2.1 Recommendations for farmers

Farmers should:

(i) diversify their activities to cope or adapt to the adverse impacts of climate change on agro-pastoral productions;

(ii) be receptive and adopt crop varieties and livestock breed that can adapt to extreme climate conditions;

(iii) systematically harvest most of the crop-residues after harvest for livestock feeding during the dry season. Also, nutrient mining through residues exportation should be counterbalanced through compost application to farms for the subsequent farming seasons.

### 7.2.2 Recommendations for policy

Policy efforts should gear towards the adoption of climate-smart initiatives, such as CLI, promoting drought-tolerant plant, drought-resistant, and short-duration crop varieties, that can adapt to extreme climate conditions, especially within the Sahel and Sudan-Sahel zones of the country. In addition, efforts should sustained education and adoption of the principle of diversification of farm activities to withstand climatic shocks. Moreover, appropriate breeding conditions should be provided to minimize the influence of non-climatic factors (stresses associated with handling, transport or housing) on livestock disease resurgence. Furthermore, policy efforts should gear toward CLI through educational, financial, technical, and conceptual supports.

### 7.2.3 Recommendations for future research

Further in-depth research is necessary on crop-livestock integration at different scales, from the smallest to the largest landscape, territorial or regional scales. The advantages and limitations and, much more, the effectiveness of each scale should be investigated and documented. Finally, further research could analyse the future impact of CLI on carbon sequestration, farm incomes, food production and related GHG emissions under different climate scenarios of Shared Socio-economic Pathways (SSPs).

## 7.3 Major contributions to knowledge

This research contributed to:

(i) establishing that increased frequency in climate extremes have resulted in more frequent resurgence in livestock diseases which negatively impact livestock productivity;

(ii) developing/updating Crop-Livestock Integration (CLI) Indicators as integration assessment tools. The following new integration indicators were designed and introduced in the assessment: integration effectiveness, the integration efficiency, total and daily efforts of integration and financial integration;

(iii) establishing the performance and implications of CLI on farming systems across the Sudan; Sudan-Sahel and Sahel agroecological zones of Burkina Faso.

### 7.4 Limitations of the study

This research limitations included:

(i) the use of emission factors of the tier 1 method (IPCC, 2006), calibrated with respect to temperate conditions could lead to emission under or over-estimation in tropical conditions.

(ii) the insufficient information on some factors needed for emissions estimation made it impossible to consider the following sources of GHGs emission: (a) $CH_4$ emission from rice cultivation; (b) $CO_2$ emissions from liming; (c) $CO_2$ emissions from livestock respiration; (d) indirect $N_2O$ emissions from manure management; (e) direct $N_2O$ emissions produced from managed organic soils; (f) emissions from other agricultural inputs, such as pesticides and seeds (considered negligible); (g) emission from the production of investment goods (machines and buildings) and those related to consumption of fossil fuels (both for on-farm and off-farm activities); indirect $N_2O$ emissions induced by leaching of $NO_3$ or $NH_3$ volatilization from managed soils were not considered.

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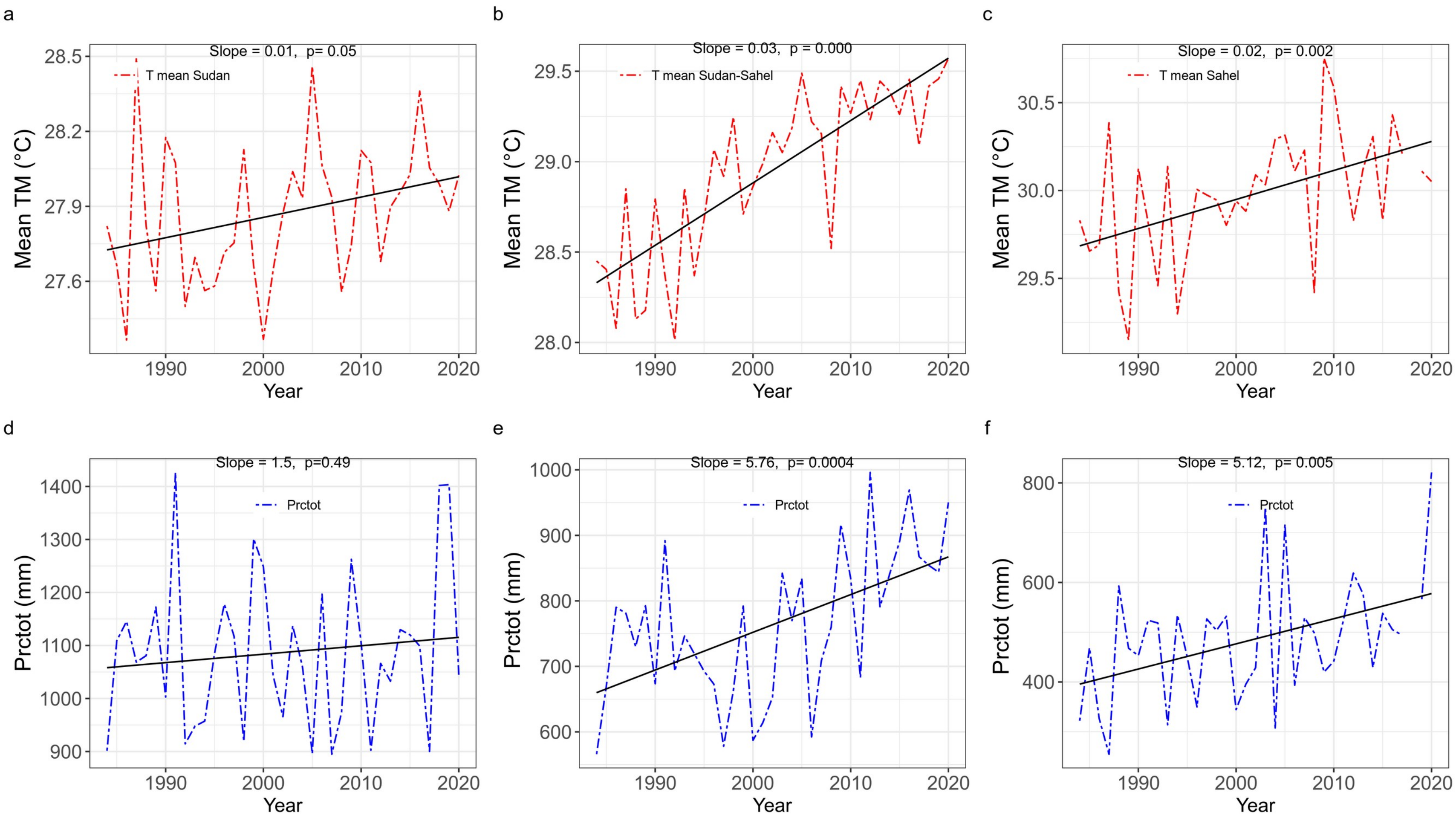
**APPENDICES**

Appendix 1: Trend of major climate indices in study sites across three climatic zones of Burkina Faso

| Indices | Frequency | Start Year | End Year | Sudan | | Sudan-Sahel | | Sahel | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Slope | P value | Slope | P value | Slope | P value |
| Tropical nights (TR) | Annual | 1961 | 2020 | 0.045 | 0.688 | 0.766 | **0.000** | 0.811 | **0.000** |
| Tropical nights (TR) | Monthly | 1961 | 2020 | 0.000 | 0.986 | 0.005 | **0.006** | 0.006 | **0.007** |
| Daily Temperature Range (DTR) | Annual | 1961 | 2020 | 0.001 | 0.731 | -0.011 | **0.000** | -0.038 | **0.000** |
| Daily Temperature Range (DTR) | Monthly | 1961 | 2020 | 0.000 | 0.798 | -0.001 | 0.061 | -0.003 | **0.000** |
| Warm spell duration indicator (WSDI) | Annual | 1961 | 2020 | 0.056 | 0.254 | 0.418 | **0.000** | 0.127 | 0.096 |
| Cold spell duration indicator (CSDI) | Annual | 1961 | 2020 | 0.649 | **0.000** | -0.056 | **0.015** | -0.074 | **0.002** |
| Standardised Precipitation Evapotranspiration Index (SPEI) | Monthly | 1961 | 2020 | 0.000 | **0.015** | 0.000 | 0.247 | 0.001 | **0.000** |
| Mean TM (TMm) | Annual | 1961 | 2020 | 0.008 | **0.001** | 0.027 | **0.000** | 0.028 | **0.000** |
| Mean TM (TMm) | Monthly | 1961 | 2020 | 0.001 | 0.077 | 0.002 | **0.000** | 0.002 | **0.000** |
| Mean TX (TXm) | Annual | 1961 | 2020 | 0.008 | **0.003** | 0.021 | **0.000** | 0.009 | **0.011** |
| Mean TX (TXm) | Monthly | 1961 | 2020 | 0.001 | 0.169 | 0.002 | **0.001** | 0.001 | 0.268 |
| Mean TN (TNm) | Annual | 1961 | 2020 | 0.008 | **0.008** | 0.032 | **0.000** | 0.047 | **0.000** |
| Mean TN (TNm) | Monthly | 1961 | 2020 | 0.001 | 0.248 | 0.003 | **0.000** | 0.004 | **0.000** |

Source: author's Own computation, 2023.




Appendix 2: Trend in average daily temperature and annual total precipitation in Sudan (a,d), Sudan-Sahel (b, e) and Sahel (c, f) zones of Burkina Faso over the period 1984-2020. Source: author's Own computation, 2023.

Appendix 3: Selected components derived from dimension reduction of climate indices in the Sudan zone

| Variables | PC1<br>Rainfall (mm) | PC2<br>Extreme hot days (%) | PC3<br>Cold nights (%) | PC4<br>Dry spell (days) |
|---|---|---|---|---|
| Very heavy rain days (R20mm) | **0.93** | -0.08 | 0.01 | 0.03 |
| Rainfall intensity (SDII) | **0.91** | -0.13 | 0.02 | -0.16 |
| Total precipitation (PRCPTOT) | **0.90** | -0.28 | 0.07 | 0.14 |
| Standardised Precipitation Index (SPI) | **0.74** | -0.03 | -0.03 | 0.10 |
| Hot days (TX90p) | -0.11 | **0.86** | -0.06 | 0.02 |
| Warm Spell Duration Indicator (WSDI) | -0.04 | **0.86** | -0.32 | 0.04 |
| Hottest day (TXx) | -0.19 | **0.77** | 0.30 | -0.15 |
| Hottest night (TNx) | -0.15 | **0.59** | -0.20 | 0.00 |
| Cold night (TN10p) | -0.14 | -0.20 | **0.91** | -0.02 |
| Coldest night (TNn) | -0.19 | 0.04 | **-0.81** | -0.12 |
| Coldest day (TXn) | -0.25 | -0.15 | 0.10 | **-0.83** |
| Consecutive dry days (CDD) | -0.19 | -0.10 | 0.16 | **0.77** |
| Consecutive wet days (CWD) | 0.03 | -0.28 | 0.51 | **0.58** |
| Cool days (TX10p) | 0.18 | -0.34 | 0.10 | 0.02 |
| Warm nights (TN90p) | 0.38 | 0.14 | -0.24 | 0.26 |
| **Eigenvalues** | **3.46** | **2.81** | **2.08** | **1.78** |
| **Variance (%)** | **0.23** | **0.19** | **0.14** | **0.12** |
| **Cumulative (%)** | **0.23** | **0.42** | **0.56** | **0.7 0** |

Legend : PC means Principal Component. Loadings above 0.5 is bolded on each principal component. Source: author’s Own computation, 2023.

Appendix 4: Selected components derived from dimension reduction of climate indices in the Sudan-Sahel zone

| Variables | PC 1<br>Extreme hot days (%) | PC 2<br>Rain intensity (mm/d) | PC 3<br>Wet spell (days) | PC 4<br>Dry and cold nights event (days) |
|---|---|---|---|---|
| Hot days (TX90p) | **0.87** | 0.09 | -0.04 | -0.14 |
| Warm Spell Duration Indicator (WSDI) | **0.77** | -0.15 | 0.25 | 0.10 |
| Hottest day (TXx) | **0.69** | 0.17 | 0.19 | 0.01 |
| Cool days (TX10p) | **-0.67** | 0.13 | 0.21 | 0.50 |
| Rainfall intensity (SDII) | 0.03 | **0.95** | 0.04 | 0.02 |
| Total precipitation (PRCPTOT) | 0.13 | **0.84** | 0.24 | -0.33 |
| Standardised Precipitation Index (SPI) | 0.53 | **0.60** | -0.09 | -0.07 |
| Hottest night (TNx) | -0.24 | **0.40** | 0.36 | -0.33 |
| Coldest night (TNn) | 0.09 | 0.02 | **-0.82** | -0.09 |
| Consecutive wet days (CWD) | 0.38 | -0.04 | **0.76** | -0.12 |
| Very heavy rain days (R20mm) | 0.30 | 0.16 | **0.66** | 0.16 |
| Coldest day (TXn) | 0.34 | -0.47 | **-0.60** | -0.14 |
| Warm nights (TN90p) | -0.01 | 0.25 | -0.14 | **-0.85** |
| Consecutive dry days (CDD) | -0.24 | 0.04 | -0.07 | **0.74** |
| Cold night (TN10p) | 0.30 | -0.49 | 0.33 | **0.61** |
| **Eigenvalues** | **3.14** | **2.75** | **2.52** | **2.22** |
| **Variance (%)** | **0.21** | **0.18** | **0.17** | **0.15** |
| **Cumulative (%)** | **0.21** | **0.39** | **0.56** | **0.71** |

Legend : PC means Principal Component. Loadings above 0.5 is bolded on each principal component. Source: author's Own computation, 2023.

Appendix 5: Selected components derived from dimension reduction of climate indices in the Sahel zone

| Variables | PC 1 | PC 2 | PC 3 | PC 4 |
|---|---|---|---|---|

| | Extreme hot night (%) | Rain intensity (mm/d) | Cold and dry days | Cold and wet days |
|---|---|---|---|---|
| Warm nights (TN90p) | **0.87** | -0.02 | -0.03 | -0.14 |
| Warm Spell Duration Indicator (WSDI) | **0.63** | -0.18 | -0.15 | 0.07 |
| Hottest night (TNx) | **0.77** | 0.19 | 0.15 | -0.25 |
| Hot days (TX90p) | **0.51** | -0.36 | 0.22 | 0.46 |
| Total precipitation (PRCPTOT) | -0.15 | **0.92** | -0.15 | 0.10 |
| Rainfall intensity (SDII) | -0.03 | **0.88** | 0.00 | -0.14 |
| Very heavy rain days (R20mm) | 0.10 | **0.79** | -0.25 | -0.25 |
| Coldest night (TNn) | 0.02 | 0.01 | **0.83** | 0.46 |
| Standardised Precipitation Index (SPI) | -0.25 | 0.22 | **-0.78** | -0.12 |
| Consecutive dry days (CDD) | -0.25 | -0.16 | **0.74** | -0.33 |
| Hottest day (TXx) | 0.54 | 0.30 | **-0.57** | 0.21 |
| Cool days (TX10p) | -0.09 | 0.31 | -0.01 | **-0.78** |
| Coldest day (TXn) | -0.30 | 0.00 | -0.02 | **0.74** |
| Consecutive wet days (CWD) | -0.45 | 0.26 | 0.43 | **0.56** |
| Cold night (TN10p) | -0.52 | 0.10 | -0.03 | **-0.53** |
| **Eigenvalues** | **3.02** | **2.78** | **2.53** | **2.52** |
| **Variance (%)** | **0.2** | **0.19** | **0.17** | **0.17** |
| **Cumulative (%)** | **0.2** | **0.39** | **0.56** | **0.72** |

Legend : PC means Principal Component. Loadings above 0.5 is bolded on each principal component. Source: author's Own computation, 2023.

Appendix 6: Secondary data used for crop-livestock water productivity and greenhouse gases emissions

| **Designations** | | **Values** | **Sources** |
|---|---|---|---|
| Livestock populations conversion to TLU | Calf | 0.25 TLU/head | https://link.springer.com/article/10.1186/s40100-017-0075-z/tables/6 |
| | Donkey | 0.7 TLU/head | |
| | Cattle | 0.70 TLU/head | FAO (2003) |
| | Sheep | 0.1 TLU/head | |
| | Goat | 0.1 TLU/head | |
| Meat production | Cattle | 52 % | FAO (1999) |
| | Sheep | 46 % | |
| | Goat | 46 % | |
| Herds' manure production | Cattle | 2.08 kg $day^{-1}$ $TLU^{-1}$ | Bidjokazo et al., (2012) Gomgnimbou et al., (2014) |
| | Sheep | 0.35 kg $day^{-1}$ $TLU^{-1}$ | |
| | Goat | 0.35 kg $day^{-1}$ $TLU^{-1}$ | |
| | Swine | 4.9g kg $day^{-1}$ | Francirose et al., (2006) |
| | Poultry | 0.055g kg $day^{-1}$ | |
| Manure nutrient content in N | Cattle | 9.0 g N $kg^{-1}$ | Fofana et al., (2012) |
| | Sheep | 14.0 g N $kg^{-1}$ | |
| | Goat | 14.0 g N $kg^{-1}$ | |
| | Swine | 38.7 g N $kg^{-1}$ | Adebayo et al., (2019) |
| | Poultry | 26.0 g N $kg^{-1}$ | |
| Manure nutrient content in P | Cattle | 4.0 g P $kg^{-1}$ | Fofana et al., (2012) |
| | Sheep | 4.0 g P $kg^{-1}$ | |
| | Goat | 4.0 g P $kg^{-1}$ | |
| Manure nutrient content in K | Cattle | 56.0 g K $kg^{-1}$ | |

| Designations | | Values | Sources |
|---|---|---|---|
| | Sheep<br>Goat | 54.0 g K $kg^{-1}$ | |
| Annual milk production | | Number of lactating cows<br>Lactation period<br>Daily milk yield in liters | Household Surveys database |
| Meat valuation (cattle, sheep, goat) | | 3.89 USD $kg^{-1}$ | Local market price from surveyed households |
| Milk valuation | Cow milk | 0.61 USD $L^{-1}$ | |
| Manure valuation | NPK bag (50kg) Dano | 32.85 USD | |
| | NPK bag (50kg) Niou | 31.99 USD | |
| | NPK bag (50kg) Dori | 38.04 USD | |
| | Urea bag (50kg) Dano | 32.85 USD | |
| | Urea bag (50kg) Niou | 30.26 USD | |
| | Urea bag (50kg) Dori | 29.39 USD | |
| Value of livestock traction service | Daily hiring cost of oxen Dano | 4.73 USD | |
| | Daily hiring cost of oxen Niou | 5.44 USD | |
| | Daily hiring cost of donkey Dano | 3.88 USD | |
| | Daily hiring cost of donkey Niou | 3.07 USD | |
| | Daily hiring cost of donkey Dori | 2.48 USD | |
| Crop and grazing feed use factors | Use factor of crop residues Dano | 73-95 % | Intake rate from survey |
| | Use factor of crop residues Niou | 76-98 % | |
| | Use factor of crop residues Dori | 87-98 % | |
| | Grazing land feed use-factor | 45 % | Amole (2021) |
| Harvest Index | HI maize | 0.4 | Bacye and Bor (2011) |

| **Designations** | | **Values** | **Sources** |
|---|---|---|---|
| | HI millet | 0.23 | |
| | HI sorghum | 0.21 | |
| | HI cowpea | 0.32 | |
| | HI groudnut | 0.36 | |
| | HI rice | 0.49 | Bueno and Lafarge (2009) |
| | HI sesame | 0.15 | Said Badshah (2017) |
| | North Sahel | 0.2TLU/ha | |
| Livestock density | South Sahel | 0.2TLU/ha | Ouédraogo K. (2011) |
| | North Sudan | 0.4TLU/ha | |
| | initial (i) | 20 days | |
| | Kc(i) | 0.3 | |
| | vegetative (z) | 33 days | |
| Crop coefficent (Kc) for Senegal sahelian rangelands | Kc(v) | 0.3-0.75 | Diouf (2016) |
| | flowering (f) | 25 days | |
| | Kc(f) | 0.75 | |
| | ripening (r) | 10 days | |
| | Kc(r) | 0.3-0.75 | |

Source: author's Own computation, 2023.

Appendix 7: Methodology of greenhouse gases estimation across three climatic zones of Burkina Faso

| Emissions type | Estimation equations | Descriptions |
|---|---|---|
| $CH_4$ emissions from enteric fermentation | (i) Enteric emission by livestock category<br>$$Emission(CH_4) = EF_T\left(\frac{N_T}{(10^6)}\right)$$<br>source: (IPCC, 2006) | Emission = methane emissions from individual livestock enteric fermentation (Gg $CH_4$ $yr^{-1}$);<br>$EF_T$ = emission factor for the defined livestock population, kg $CH_4$ $head^{-1}$ $yr^{-1}$;<br>$N_T$ = the number of head of livestock species / category T in the country;<br>T = species/category of livestock |
| | (ii) Total methane emissions from households' herds Enteric Fermentation<br>$$Total\,CH_{4\,Enteric} = \sum E_i$$<br>source: (IPCC, 2006) | Total $CH_{4Enteric}$= total methane emissions from Enteric Fermentation, $GgCH4yr^{-1}$ ;<br>$E_i$ = is the emission for the $i^{th}$ livestock categories and subcategories. |
| $N_2O$ and $CH_4$ emissions from animal manure management | (i) $CH_4$ emissions from animal manure<br>$$CH_{4\,Manure} = \frac{\sum (EF_{(T)} N_{(T)})}{10^6}$$<br>source: (IPCC, 2006) | $CH_{4Manure}$ = CH4 emissions from manure management, for a defined population, Gg $CH_4 yr^{-1}$;<br>$EF_{(T)}$ = emission factor for the defined livestock population, kg $CH_4$ $head^{-1} yr^{-1}$ ;<br>$N_{(T)}$ = the number of head of livestock species per category T in the zone;<br>T = species per category of livestock. |

| | | |
|---|---|---|
| | (ii) $N_2O$ emissions from animal manure management<br><br>$N_2O(mm) = N_{EMMS}\, EF_{3(S)} \frac{44}{28}$<br><br>$N_{EMMS} = N_{(T)} Nex_{(T)} MS_{(T,S)}$<br><br>$Nex_{(T)} = (N_{rate(T)} TAM\, 10^{-3})\, 365$<br><br>source: (IPCC, 2006) | $N_2O(mm)$ =Annual direct $N_2O$ emissions from Manure Management;<br><br>$N_{EMMS}$ = Total nitrogen excretion for the MMS;<br><br>$N_{(T)}$ = the number of head of livestock species per category T in the zone;<br><br>$MS_{(T,S)}$=Fraction of total annual nitrogen excretion managed in MMS for each species/livestock category;<br><br>$Nex_{(T)}$ = Annual N excretion per head of species/livestock category;<br><br>$N_{rate(T)}$ = Default N excretion rate;<br><br>TAM = Typical animal mass for livestock category |
| $CO_2$, $N_2O$ and $CH_4$ emissions related to the use synthetic fertilizer (Urea, NPK) | (i) $CO_2$ Emissions from Urea Fertilization :<br><br>$CO_2 - C\, Emission = M\,(EF)$<br><br>source: (IPCC, 2006) | CO2-C Emission =Annual $CO_2$-C emissions from urea fertilization;<br><br>M = Annual amount of Urea Fertilization (t urea $yr^{-1}$) ;<br><br>EF = emission factor, tonne of C (tonne of urea)$^{-1}$ |
| | (ii) $N_2O$-N emissions from managed soils (NPK and Urea fertilization) :<br><br>$N_2O - N_{N\,inputs} = F\,(EF)$<br><br>source: (IPCC, 2006) | $N_2O$-$N_{N\ inputs}$ =Annual direct $N_2O$-N emissions produced from managed soils;<br><br>F = Annual amount of N synthetic fertilizers applied;<br><br>EF = Emission factor for $N_2O$ emissions from N inputs |

| | | |
|---|---|---|
| Direct $N_2O$ emissions from dung inputs to grazed soils | $N_2O-N_{PRP}=F_{PRP}EF_{3\,PRP}$<br><br>source: (IPCC, 2006) | $N_2O$-$N_{PRP}$ = Annual direct $N_2O$ emissions from dung inputs to grazed soils;<br><br>$EF_{3PRP}$ = Emission factor for $N_2O$ emissions from dung N deposited on pasture, range and paddock by grazing animals;<br><br>$F_{PRP}$ = Amount of dung N deposited by grazing animals on pasture, range and paddock. |

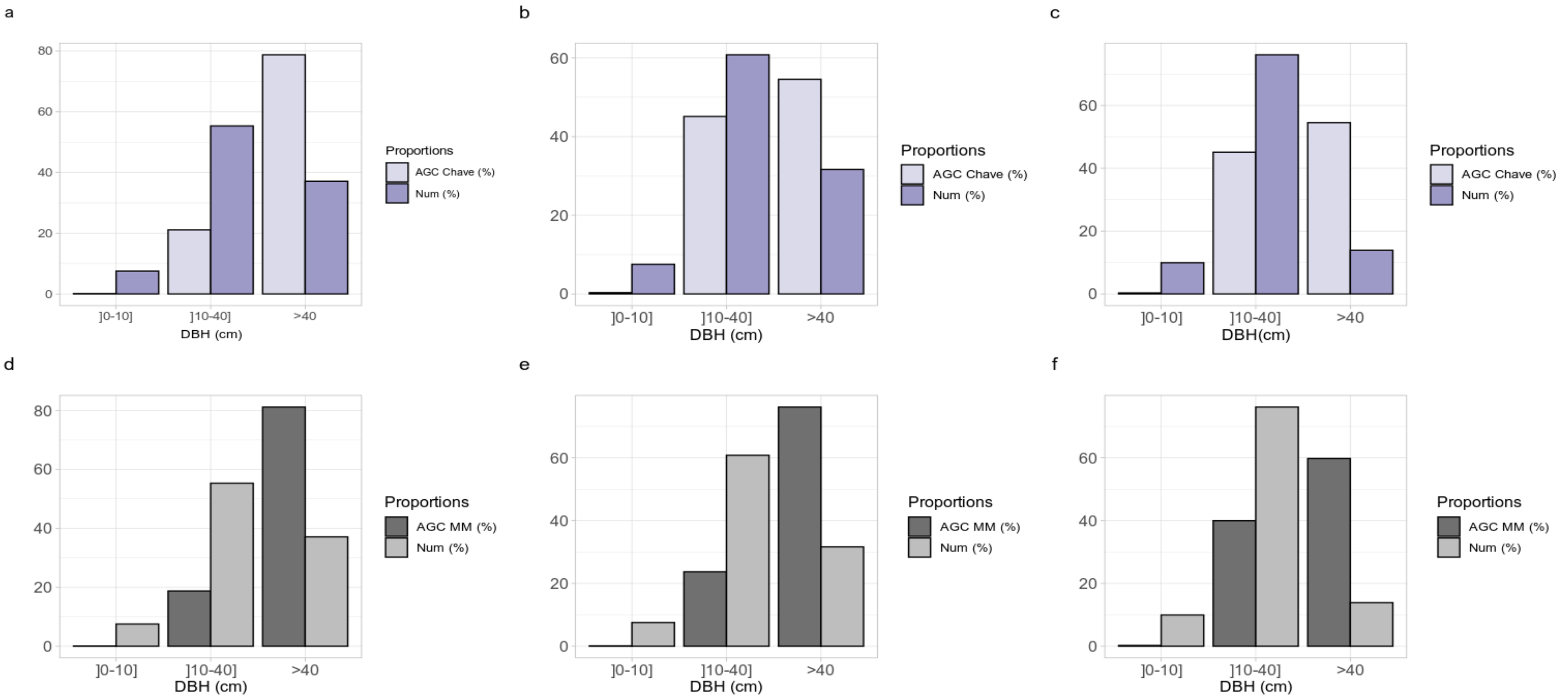
Source: author's Own computation, 2023.

Appendix 8: Effects of stand diversity and density on plot level aboveground carbon density computed from the mixed model.

| Study Zones | Models | Predictors | α | SE | t value | Pr (>t) | Adj.R2 (%) | p-value |
|---|---|---|---|---|---|---|---|---|
| South Dano (Sudan zone) | Tree density + Richness | Intercept | 2.98595 | 1.13276 | 2.636 | 1.08E-02 | 30.77 | 3.59E-04 |
| | | Tree density | 0.14557 | 0.03564 | 4.085 | 0.00014 | | |
| | | Richness | 0.39764 | 0.20953 | 1.898 | 0.06279 | | |
| | Tree density + Shannon | Intercept | 2.23954 | 1.07652 | 2.08 | 4.20E-02 | 37.06 | 3.65E-04 |
| | | Tree density | 0.15006 | 0.03264 | 4.597 | 2.43E-05 | | |
| | | Shannon | 2.73604 | 0.88022 | 3.108 | 0.00293 | | |
| | Tree density + Simpson | Intercept | 2.15679 | 1.10725 | 1.948 | 0.05636 | 36.62 | 4.18E-04 |
| | | Tree density | 0.1514 | 0.03271 | 4.629 | 2.17E-05 | | |
| | | Simpson | 5.63372 | 1.8582 | 3.032 | 0.00365 | | |
| Niou (Sudan-Sahel zone) | Tree density + Richness | Intercept | 2.10793 | 1.35871 | 1.551 | 0.126 | 29.01 | 2.15E-05 |
| | | Tree density | 0.15187 | 0.03164 | 4.8 | 1.19E-05 | | |
| | | Richness | 0.10275 | 0.19143 | 0.537 | 0.594 | | |
| | Tree density + Shannon | Intercept | 4.57562 | 1.77135 | 2.583 | 0.0124 | 30.46 | 1.19E-05 |
| | | Tree density | 0.15 | 0.03078 | 4.874 | 9.12E-06 | | |
| | | Shannon | -1.39083 | 1.14265 | -1.217 | 0.2285 | | |
| | Tree density + Simpson | Intercept | 5.5075 | 1.9235 | 2.863 | 0.00586 | 31.84 | 6.75E-06 |
| | | Tree density | 0.1444 | 0.0309 | 4.674 | 1.85E-05 | | |
| | | Simpson | -4.3325 | 2.6551 | -1.632 | 0.10825 | | |
| Dori (Sahel zone) | Tree density + Richness | Intercept | 2.77872 | 0.80274 | 3.462 | 0.00102 | 21.64 | 3.59E-04 |
| | | Tree density | 0.09554 | 0.02234 | 4.276 | 7.32E-05 | | |
| | | Richness | -0.22457 | 0.15127 | -1.485 | 0.14318 | | |
| | Tree density + Shannon | Intercept | 3.1223 | 1.00547 | 3.105 | 0.002959 | 21.6 | 3.65E-04 |
| | | Tree density | 0.08704 | 0.02101 | 4.142 | 0.000115 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Shannon | -1.04664 | 0.70987 | -1.474 | 0.145875 | | |
| | Tree density + Simpson | Intercept | 3.52867 | 1.3348 | 2.644 | 0.010576 | 21.22 | 4.18E-04 |
| | | Tree density | 0.08193 | 0.02099 | 3.903 | 0.000254 | | |
| | | Simpson | -2.56481 | 1.86495 | -1.375 | 0.174429 | | |

α, SE and Adj. R2 represent estimates of regression coefficients, standard error of means and percent adjusted R2, respectively. Source: author's Own computation, 2023.




Appendix 9: Variations in aboveground carbon density and woody species between diameter class in the Sudan (a and d), the Sudan-Sahel (b and e), and Sahel (c and f) zones of Burkina Faso following Pantropical model (a, b, c) and Mixed model (d, e, f). Legend : AGC Chave is the Aboveground carbon stock computed from the Chave et al., (2014); AGC MM is the Aboveground carbon stock computed from the mixed local model (Ganamé et al. 2021). Source: author's Own computation, 2023.

Appendix 10: List of agroforestry woody species across climatic zones

| Species names | Family | Occurrence zone |
|---|---|---|
| Acacia macrostachya Rchb. ex DC. | Fabaceae | II |
| Acacia nilotica (L.) Willd. ex Delile | Fabaceae | I, II,III |
| Acacia senegal (L.) Willd. | Fabaceae | I, II,III |
| Acacia seyal Delile | Fabaceae | I, II,III |
| Acacia sieberiana DC. | Fabaceae | II, III |
| Acacia tortilis (Forssk.) Hayne | Fabaceae | I |
| Adansonia digitata L. | Malvaceae | I, II,III |
| Afzelia africana Sm. | Fabaceae | III |
| Albizia chevalieri Harms | Fabaceae | II |
| Anacardium occidentale L. [cult.] | Anacardiaceae | III |
| Anogeissus leiocarpa (DC.) Guill. & Perr. | Combretaceae | II, III |
| Azadirachta indica A.Juss. [cult.] | Meliaceae | I, II,III |
| Baissea multiflora A.DC. | Apocynaceae | II |
| Balanites aegyptiaca (L.) Delile | Zygophyllaceae | I, II |
| Bauhinia rufescens Lam. | Fabaceae | I |
| Bombax costatum Pellegr. & Vuill. | Malvaceae | II, III |
| Bridelia scleroneura Müll.Arg. | Phyllanthaceae | II |
| Burkea africana Hook. | Fabaceae | III |
| Calotropis procera (Aiton) R.Br. | Apocynaceae | III |
| Cassia sieberiana DC. | Fabaceae | II |
| Combretum glutinosum Perr. ex DC. | Combretaceae | I, II,III |
| Combretum micranthum G.Don | Combretaceae | II |
| Commiphora africana (A.Rich.) Engl. | Burseraceae | I, II |
| Cordia myxa L. | Boraginaceae | I,III |
| Daniellia oliveri (Rolfe) Hutch. & Dalziel | Fabaceae | II, III |
| Detarium microcarpum Guill. & Perr. | Fabaceae | II, III |
| Dichrostachys cinerea (L.) Wight & Arn. | Fabaceae | III |
| Diospyros mespiliformis Hochst. ex A.DC. | Ebenaceae | I, II,III |
| Eucalyptus camaldulensis Dehnh. [cult.] | Myrtaceae | II |
| Faidherbia albida (Delile) A.Chev. | Fabaceae | I, II,III |
| Feretia apodanthera Delile | Rubiacaee | II |
| Ficus iteophylla | Moraceae | II |
| Ficus platyphylla Delile | Moraceae | III |
| Ficus sycomorus L. | Moraceae | II, III |
| Ficus thonningii Blume | Moraceae | II |
| Flacourtia indica (Burm.f.) Merr. | Salicaceae | III |
| Gardenia aqualla Stapf & Hutch. | Rubiacaee | II |
| Gardenia erubescens Stapf & Hutch. | Rubiacaee | II |

| | | |
|---|---|---|
| Gardenia ternifolia Schumach. & Thonn. | Rubiacaee | II |
| Gmelina arborea Roxb. [cult.] | Lamiaceae | III |
| Hyphaene thebaica (L.) Mart. | Arecaceae | I |
| Isoberlinia doka Craib & Stapf | Fabaceae | III |
| Khaya senegalensis (Desr.) A.Juss. | Meliaceae | II, III |
| Lannea acida A.Rich. | Anacardiaceae | II, III |
| Lannea microcarpa Engl. & K.Krause | Anacardiaceae | I, II,III |
| Lannea velutina A.Rich. | Anacardiaceae | III |
| Maerua crassifolia Forssk. | Capparaceae | I |
| Mangifera indica L. [cult.] | Anacardiaceae | II, III |
| Mitragyna inermis (Willd.) Kuntze | Rubiacaee | II |
| Moringa oleifera L. | Moringaceae | III |
| Parkia biglobosa (Jacq.) R.Br. ex G.Don | Fabaceae | II, III |
| Piliostigma reticulatum (DC.) Hochst. | Fabaceae | I, II |
| Prosopis africana (Guill. & Perr.) Taub. | Fabaceae | II, III |
| Prosopis juliflora (Sw.) DC. | Fabaceae | I |
| Pterocarpus erinaceus Poir. | Fabaceae | II, III |
| Pterocarpus lucens Lepr. ex Guill. & Perr. | Fabaceae | II, III |
| Sclerocarya birrea (A.Rich.) Hochst. | Anacardiaceae | I, II |
| Securidaca longipedunculata Fresen. | Polygalaceae | II |
| Sterculia setigera Delile | Malvaceae | II, III |
| Stereospermum kunthianum Cham. | Bignoniaceae | II, III |
| Strychnos spinosa Lam. | Loganiaceae | III |
| Tamarindus indica L. | Fabaceae | II, III |
| Tectona grandis L.f. [cult.] | Lamiaceae | III |
| Terminalia avicennioides Guill. & Perr. | Combretaceae | II, III |
| Terminalia laxiflora Engl. & Diels | Combretaceae | III |
| Terminalia macroptera Guill. & Perr. | Combretaceae | II, III |
| Vitellaria paradoxa C.F.Gaertn. | Sapotaceae | II, III |
| Vitex doniana Sweet | Lamiaceae | II, III |
| Ximenia americana L. | Ximeniaceae | II |
| Ziziphus mauritiana Lam. | Rhamnaceae | I, II |

I : Sahel zone ; II : Sudan-sahel zone ; III : Sudan zone.

Source: author's Own computation, 2023.

Appendix 11: Farming households characteristics across climatic zones

| **Integration variables** | **Dano** | **Niou** | **Dori** |
|---|---|---|---|
| Household head age (year) | 45±11[a] | 49±11[b] | 47±13[a] |
| Workforce (worker) | 6±4[a] | 6±3[b] | 5±3[a] |
| Household size (person) | 10±6[a] | 13±6[b] | 11±5[c] |
| Hoe (n) | 9±8[a] | 7±3[b] | 4±2[c] |
| Plough (n) | 1±1[a] | 1±1[b] | - |
| Compost pit | < 1[a] | < 1[a] | - |
| Cart (n) | < 1[a] | < 1[b] | <1[c] |
| Farm size (ha) | 5.7±4.1[a] | 4.2±2.2[b] | 3.9±2.4[a] |
| Cattle (n) | 5.4±10.5[a] | 1.5±2.5[b] | 3.2±3.7[a] |
| Oxen (% of cattle size) | 33.4 | 23.8 | - |
| Ruminants (TLU) | 4.8±4.6[a] | 2.4±2.4[b] | 2.8±2.7[b] |
| Swine (n) | 5.5±4.7[a] | 4.8±4.1[b] | - |

Means±sd with different superscript along the lines differ significantly. Signif. Codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Legend : nb = number. Source: author's Own computation, 2023.

Appendix 12: Questionnaire used in primary data collection

Source: author's Own compilation, 2023.

**1. General information**

1.1. Household code: ..................................................................

1.2. Village:..........................................................................

1.3. GPS location: Long:......................../Latitude:.......................Altitude:...............

1.3.1. Name & Surname of household head: ……………………………..

1.3.2. Phone number: ..............................................

1.3.3. Age :........................................................

1.3.4. Sex :.......................................................

1.3.5. Marital status:...........................................................

1.3.6. Citizen status: Native .......................... Migrant.........................

1.3.7. Education : primary /--/ junior high /--/ senior high /--/ Franco-arabe/--/ Non-formal/--/ other /--/

**2. Land tenure**

| Land possession | | Yes | No |
|---|---|---|---|
| Owner | Inheritance | | |
| | Purchase | | |
| | Gift/Donation | | |
| Loan | | | |
| Rental | | | |

**3. Farming practices**

| **Practices** | | **Responses** |
|---|---|---|
| Cropped area expansion | Yes/No | |
| Crop association | Yes/No | |
| | Crop type | |
| Crop rotation | Yes/No | |
| | Crop type | |
| | Frequency | |
| Fallow | Yes/No | |
| | Frequency | |
| Water conservation methods | Yes/No | |
| | Stone bunds | |
| | "Zai" | |
| | Half-moons | |
| | other | |
| Manure management | Storage in solid form | |
| | Liquid/Slurry | |
| | Spreading | |
| | autres | |

**4. Productions**

| Livestock category | Number | Production of milk | Egg productions | Meat production |
|---|---|---|---|---|
| Calf | | | | Meat production will be estimated using data from litterature |
| Cow male | | | | |
| Cow female | | | | |
| Milking cow | | | | |
| Sheep | | | | |
| Goat | | | | |
| Pigs | | | | |
| Donkey | | | | |
| Chicken | | | | |
| Guinea fowl | | | | |
| other1: | | | | |
| other 2: | | | | |
| other 3: | | | | |
| other 4: | | | | |
| *NB: Other : turkeys, duck, horse, camel* | | | | |

**5. Crop-livestock integration**

| Integration criteria | | Integration factors | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Livestock feeding** | | | | | | | | | |
| Type of forage | | Corn straw | Sorghum straw | Rice straw | Cowpea haulm | Groundnut haulm | Hay | Cowpea pods | Maize husk |
| Total quantity stocked (local unit/Kg) | | | | | | | | | |
| Unitary cost (FCFA) | | | | | | | | | |
| Stock value (FCFA) | | | | | | | | | |
| Duration of stored forage (month) | | | | | | | | | |
| Type of concentrate feed | | Cotton cake | Soybean cake | Cereal bran | Distiller's grain | Pigeon pea | *F. albida* | | |
| Quantity purchased (bag of 50Kg) | | | | | | | | | |
| Estimated cost (FCFA) | | | | | | | | | |
| **Farm fertilisation** | | Dung | Compost | Household refuse | | | | | |
| Quantity of organic manure mobilised (local unit: cartload) | | | | | | | | | |
| Manure estimated cost (FCFA) | | | | | | | | | |
| | | | | | | | | | |
| **Draft-power** | | Oxen | Donkey | | | | | | |
| Draft animal used for ploughing | Number | | | | | | | | |
| | Number of days | | | | | | | | |
| | Number hours/day | | | | | | | | |
| | Daily hiring cost | | | | | | | | |
| | Area ploughed | | | | | | | | |
| Draft animal used for | | Oxen | Donkey | | | | | | |
| | Number | | | | | | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| weeding | Number of days | | | | | | | | |
| | Number hours/day | | | | | | | | |
| | Daily hiring cost | | | | | | | | |
| | Area weeded | | | | | | | | |
| | | Oxen | Donkey | | | | | | |
| Draft animal used for the transport of residues | Number | | | | | | | | |
| | Number of days | | | | | | | | |
| | Number hours/day | | | | | | | | |
| | Daily hiring cost | | | | | | | | |
| | Qty transported | | | | | | | | |
| | | Oxen | Donkey | | | | | | |
| Draft animal used for the transport of manure | Number | | | | | | | | |
| | Number of days | | | | | | | | |
| | Number hours/day | | | | | | | | |
| | Daily hiring cost | | | | | | | | |
| | Qty transported | | | | | | | | |
| **Incomes re-investment** | | Purchase of livestock | Purchase of feed | Veterinary care | Purchase of chemical fertilizer | Purchase of insecticide | Purchase of herbicide | Purchase of farm tools | Part-time Worker hiring |
| Use of livestock income in cropping | | | | | | | | | |
| Amount used (FCFA) | | | | | | | | | |
| Use of use of income from cropping in breeding | | | | | | | | | |
| Amount used (FCFA) | | | | | | | | | |
| Integration practice adopted | | Crop | Animal | Animal | Cropping | livestock | | | |

| | | residues utilisation | manure utilisation | draw power utilisation | revenues reinvestment in livestock production | revenues reinvestment in crop production | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Household efforts in crop-livestock integration** | | Number of workers | Number of working day | Daily wage (FCFA) | | | | | |
| Composting | Pit digging | | | | | | | | |
| | Pit filling, watering, turning | | | | | | | | |
| | Pile composting as (filling, watering, turning | | | | | | | | |
| Household efforts in crop-livestock integration through organic manure collection and transportation (compost, dung, Park crumbs, refuse) | | | | | | | | | |
| Household efforts in crop-livestock integration through organic manure spreading (compost, dung, Park crumbs, refuse) | | | | | | | | | |
| Household efforts in crop-livestock integration through forage collection and transportation and storage | | | | | | | | | |
| Household efforts in crop-livestock integration through forage rationing | | | | | | | | | |

**Questionnaire : Part 2**

**Source: author's Own compilation, 2023.**

**Date: /........./........../............./**

1. General information ; 1.1. Household code::: ...........1.2. Name & Surname of household head : ..........…; 1.3. Phone number: ..............................

**2. Demography**

| | | | |
|---|---|---|---|
| **Household composition** | Children [0-7[ year | | |
| | Male [7-15 [year | | |
| | Female [7-15[year | | |
| | Male de [15-59[year | | |
| | Female de [15-59[year | | |
| | Male [60 et + [year | | |
| | Female [60 et + [year | | |
| | Total male | | |
| | Total female | | |
| | Number of person in charge | Male [7-15 [year | |
| | | Female [7-15[year | |
| | | Male de [15-59[year | |
| | | Female de [15-59[year | |
| | | Male [60 et + [year | |
| | | Male [7-15 [year | |
| | | Female [60 et + [year | |
| | Workforce beyond 12 year old | | |
| | Inactive below 12 years | | |
| | Number of children at school | | |
| | Total member of the household | | |

1.1. **3. Equipment**

| **Type of equipment in crop farming** | **Quantity owned** | **Quantity loaned** |
|---|---|---|
| Hoes | | |
| Plough | | |
| Cart | | |
| Ploughing tractor | | |
| Seeder | | |
| Harvest machine | | |
| Spreader | | |
| Compost pit | | |
| Other | | |
| **Type of equipment in livestock rearing** | | |
| Feeder | | |
| Drinker | | |
| Shovel | | |
| Wheelbarrow | | |
| Other | | |

**4. Crop type and management**

| Crop type *(list 5 major)* | Area cropped *(En ha)* | Seeds (kg/ha) | | | Qty of NPK used (kg) | Qty of urea used (kg) | Organic matter(kg) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Barn | Gift | Purchased | | | Produced | Purchased | Sold |
| Maize | | | | | | | | | |
| Millet | | | | | | | | | |
| Sorghum | | | | | | | | | |
| Rice | | | | | | | | | |
| Cowpea | | | | | | | | | |
| Groundnut | | | | | | | | | |
| Sesame | | | | | | | | | |
| Cotton | | | | | | | | | |

**5. Production**

| Crop products and residues management | Major crop types | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Maize** | **millet** | **Sorghum** | **Rice** | **Cowpea** | **Groundnut** | **Sesame** |
| Production *(bag of 100 kg)* | | | | | | | |
| Quantity self consumed *(bag of 100 kg)* | | | | | | | |
| Quantity sold *(bag of 100 kg)* | | | | | | | |
| Proportion of crop residue used for feeding[1] | | | | | | | |
| Proportion of crop residue used for energy | | | | | | | |
| Proportion of crop residue used in composting | | | | | | | |

1 In percentage

**6. Livestock feeding**

| Herd | | Herd size | Feeding of cattle, sheep, goat, donkey, horse (Cart, Tricycle) : (1) Maize straw ; 2) Sorghum straw ; 3) Groundnut haulm; 4) Cowpea haulm ; 5) Rice straw ; 6) Natural fodder ; 7) Agricultural by-products ; 8) Mineral and Vitamine Complex; 9) Cowpea pods ; 10) Fodder tree; 11) Seed of *F. albida* | | |
|---|---|---|---|---|---|
| | | | **November-February** | **March-June** | **July-October** |
| Cattle | Adult | | | | |
| | Young | | | | |
| Sheep | Adult | | | | |
| | Young | | | | |
| Goat | Adult | | | | |
| | Young | | | | |
| Donkey/ Horse | Adult | | | | |
| | Young | | | | |
| **Swine and chicken feeding** (Kg, pile of fodder) : 1) grain ; 2) grass ; 3) Cereal bran (rice, maize, sorghum) ; 4) Concentrate feeds; 5. Cereal ; 6. Termites; | | | | | |
| Swine | Adult | | | | |
| | Young | | | | |
| Chicken | Adult | | | | |
| | Young | | | | |

**7. Incomes generation activities**

| Off-farm activities | Revenues (CFA/y) |
|---|---|
| Crafts | |
| Fishing | |
| Trade | |
| Transport | |
| Timber and Non timber Forest Products | |
| Salaried work | |
| Emigration | |
| Gold mining | |
| Herdsman | |
| Vegetable production | |

**8. Workforce management**

| Workforce type | Contract type | | | | Wage in FCFA |
|---|---|---|---|---|---|
| | Monthly | Yearly | Occasional | Number of contracts | |
| Herdsman | | | | | |
| Crop farming | | | | | |

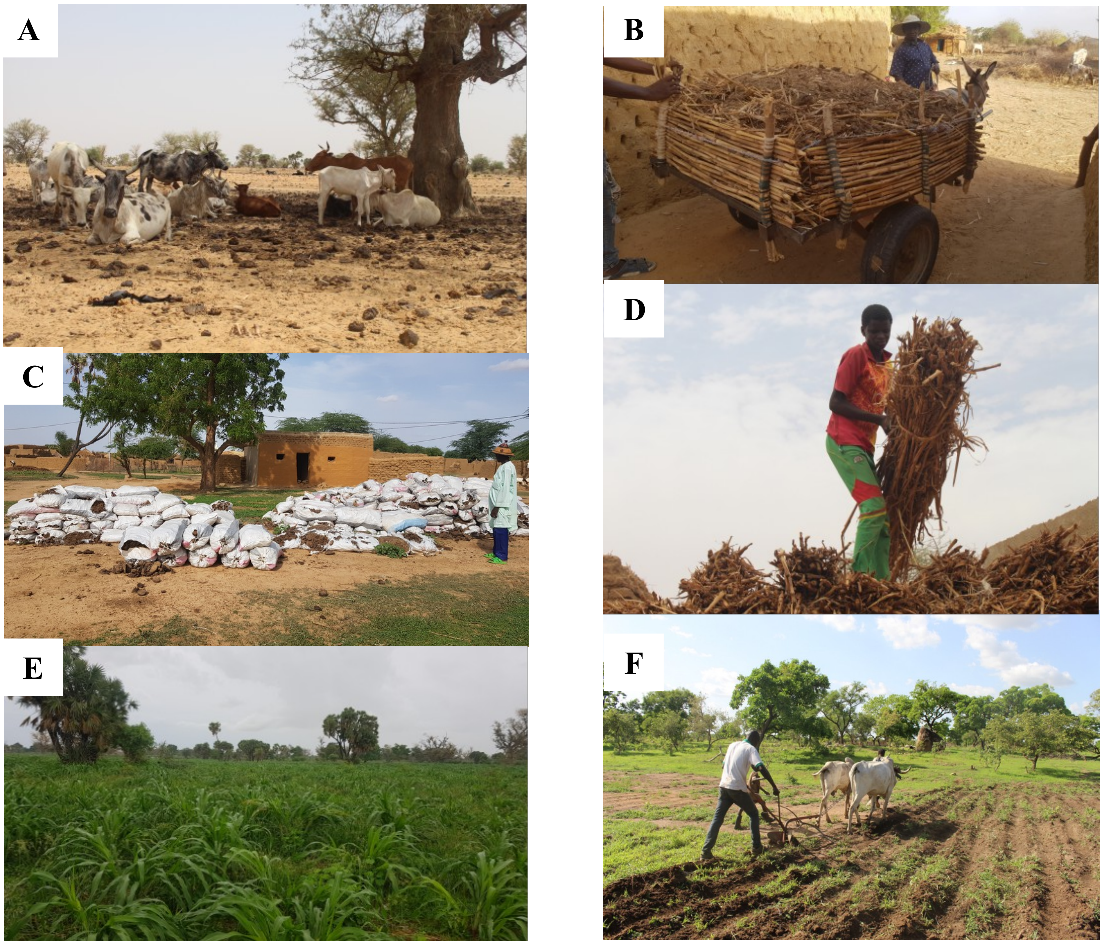
**9. Production and management in livestock breeding**

| Production | | Cattle | Sheep | Goat | Donkey /horse | Swine | Chicken |
|---|---|---|---|---|---|---|---|
| Self consumption | | | | | | | |
| Quantity | Sold | | | | | | |
| | Amount (FCFA) | | | | | | |
| Quantity | Purchased | | | | | | |
| | Amount (FCFA) | | | | | | |
| Quantity borrowed | | | | | | | |
| Health care (FCFA) | | | | | | | |

Appendix 13: Field note for dendrometric measurements

Date:………………………Name:………………………Phone number: ………………….
Commune:………………Village…………………Farm N°………………………………
GPS coordinate (Plot) :
Longitude …………………..… Latitude ………...…………Altitude (m)…………………….
Farmland area: ……….……………………
Farmland size: ……………………..

| Code | Scientific names | C130 | C20 | H1er | Ht |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |




Appendix 14: Overview on crop-livestock integration across climatic zones in Burkina Faso. A: View on passive fertility transfer by cattle herd resting under a *Faidherbia albida* (Delile) A.Chev. tree in the Sahel zone. B. Transport of manure as part of active integration. C. Collection of manure in bag of 100 kg, to be transported into the farm. D. Removing pile of sorghum straw for livestock feeding as part of active integration. E. View on a millet farm fertilized only by manure. F. ploughing by oxen as part of integration practices observed in the Sudan zone of Burkina Faso. Source: author's Own compilation, 2023.