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Assessing crop–livestock water productivity in mixed-farming systems across climatic zones of Burkina Faso

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ABSTRACT

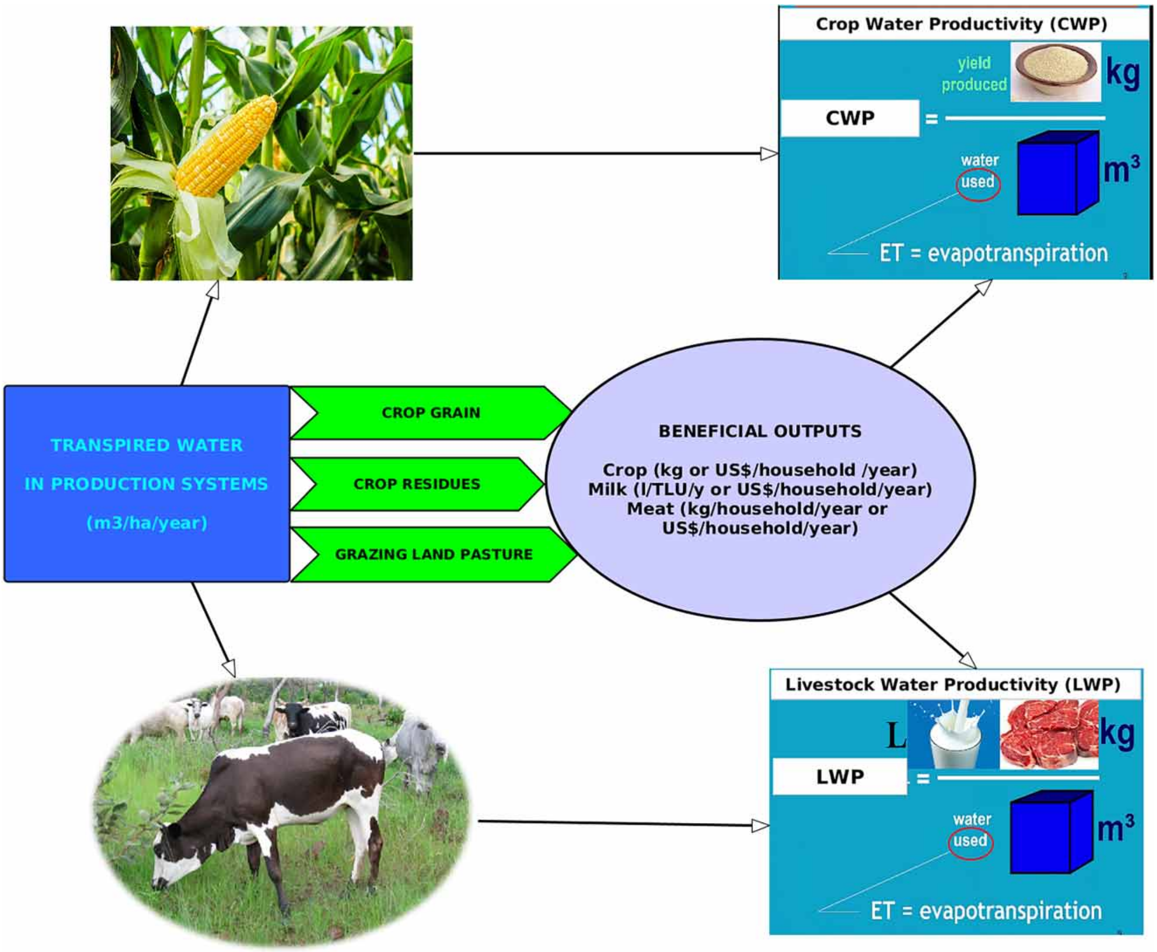
Climate change adversely impacts food and feed production, depletes water, and increases the vulnerability of the people living within arid and semi-arid areas. The current study aims to assess crop–livestock water productivity within such drought-recurrent or water-stressed regions. This was done through secondary data collection and interviews from 589 households across the Sudan, Sudan–Sahel, and Sahel climatic zones of Burkina Faso. The findings confirm that the feeding strategies of livestock were based essentially on natural pasture, crop residues, and agricultural by-products. Moreover, crop–livestock total water productivity (TWP) was found generally higher in the Sudan zone (0.29 ± 0.02 $US/m^3) characterized by more favorable climatic conditions than the Sudan–Sahel and Sahel regions that experienced a similar TWP (0.21 ± 0.01 $US/m^3). The research gives insight into the valuation of virtual water contained in livestock feeds. Improving the accessibility in quantity and quality of such feeds through informed policy actions could enhance returns on transpired water. Additionally, other water harvesting and conservation methods are also essential to sustain more productive crop–livestock systems within water-stressed regions like Burkina Faso.

Key words: evapotranspired water, mixed-crop–livestock system, water productivity

HIGHLIGHTS

- Water productivity in the mixed-crop–livestock system varied with the climatic gradient from the Sudanian zone to the Sahelian zone.
- Appropriate use of virtual water contained in crop residues contributes to better-transpired water productivity.
- Policy actions must support accessibility in quantity and quality to animal feed to ensure more yields per drop of water.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water availability in West Africa varies due to factors like climate change, population growth, and infrastructure development, impacting regional development efforts. Agriculture, the region's largest economic sector, heavily depends on rainfall and surface water sources (Rameshwaran *et al.* 2021). However, rainfall patterns and climate change affects water availability levels during the dry season (Yira *et al.* 2016). The uneven distribution of water, the impacts of climate change, and the consequences of higher temperatures are limiting factors for water availability for crop production within the study area.

Climate change significantly impacts sustainable development globally, particularly affecting agriculture (Heubes *et al.* 2013; Nelson *et al.* 2018; Sanou *et al.* 2023), water accessibility, and livelihoods (Jones & Thornton 2009) in West Africa, including Burkina Faso. These changes could lead to agricultural yield losses (El Bilali 2021) and alter rainfall patterns, posing challenges to water availability, and threatening regional food security.

West Africa's economic value stems from its abundant natural resources, strategic geographical location, and vibrant demographic. The region is rich in resources (oil, gold, diamonds, cocoa, and coffee) which drive its economy. Its proximity to the Atlantic Ocean enables access to global markets, fostering growth in industries. With a large and youthful population, West Africa benefits from a significant labor force that propels its economic expansion. This population confronts challenges stemming from political instability, insecurity, and displacement. Simultaneously, they also reap the benefits of a rich cultural heritage, economic opportunities, and efforts toward regional cooperation. Thus, the socio-economic landscape of the region presents both challenges and opportunities, shaping the overall well-being and progression of its population.

Agriculture in the Sahelian region remains highly vulnerable to climate change and variability that adversely reduces the availability of suitable land for food production or grazing, depletes water, and increases the vulnerability of the people living in the region (Amole *et al.* 2021). Most 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 (ET), will affect the following element in agricultural ecosystems: crops, livestock, trees, fish, rural communities, and physical infrastructure (Palombi & Sessa 2013). For this reason, climate change adaptation strategies for agriculture will need to be viewed through a 'water lens' (Palombi & Sessa 2013).

Despite its importance, water resource has been exposed to an unprecedented depletion and degradation worldwide. This is due to the highly diversified (Molden *et al.* 2007) and increased amount of water use (Descheemaeker *et al.* 2010). Indeed, water is the object of high competition between agricultural, industrial, household, and environmental uses. The demand for water is increasing with abstraction exceeding the natural recharge over extensive areas; and over a long period of time, groundwater is being depleted (Wada *et al.* 2010) and other water bodies are affected by pollution from agriculture, cities, and industries, thus reducing the amount of water available for use (Mekuria *et al.* 2021).

The increasing demands for food of a growing population lead to more stress on natural resources including stress on water resources (Wright 2013) to provide necessary goods and services to meet human needs, in an already water-stressed environment (Amole *et al.* 2021). These pressures are likely to be exacerbated in the context of climate change leading to more harsh environmental conditions in the tropics. This has to do with drier conditions for the production of rain-fed agriculture and grazing lands. In such conditions, there is an urgent necessity worldwide to better manage water resources (Gebreselassie *et al.* 2009) and improve water productivity in a sustainable manner (Delgado *et al.* 2001), especially in the agriculture sector. Water productivity is a concept developed since the mid-1990s around the slogan of 'crop per drop' (Zoebl 2006) and still remains at the centre of research interest worldwide, due to the key role played by water in the production systems, especially within Sahelian ecosystems. Water productivity is the amount of beneficial output per unit of water depleted expressed as a ratio of livestock products and services (meat, milk, traction, hides, manure) to the amount of water depleted in producing them (Amede *et al.* 2009). In its broadest sense, it reflects the objectives of producing more food, and the associated income, livelihood, and ecological benefits, at a lower social and environmental cost per unit of water used (Molden *et al.* 2007). Improving water productivity means producing more per drop of water and this is of great interest for areas with recurrent drought like most of the Sub-Saharan African (SSA) countries characterized by arid and semi-arid areas, where climate change is adding more burden on already stressed water resources (Nkiaka *et al.* 2021). In a perspective of coping with and minimizing the impact of water scarcity, adequate actions are necessary from both farmers and policymakers. For FAO (2012)[1], options to cope with water scarcity in agriculture can be seen as running a spectrum from the source of water to end users, and beyond, to consumers of agricultural goods. These options, whether technical, managerial, legal, and/or investment must be combined to help farmers to produce more from less water (Palombi & Sessa 2013). Water management must, therefore, be at the heart of climate change adaptation options, particularly in rural areas and in agriculture where the role of water is critical to crop–livestock production.

Such options could consist of a set of agricultural practices aiming at reducing water losses through evaporation; increasing agricultural soil water-holding capacities, maintaining and replenishing soil fertility, and valuation of virtual water contained in crop residues and hay through livestock grazing. All these actions can contribute to the improvement of crop and livestock water productivity (LWP) within drier mixed-farming systems which is of interest to the current research. Water-saving actions within drought-prone regions include the technologies of *Zaï*; half-moons (*demi lunes*), assisted natural regeneration, organic fertilization, etc. All these technologies contribute to increasing soil water retention and agricultural land fertility and definitely in improving production and water productivity.

In Burkina Faso, studies have been conducted on water productivity (Bama *et al.* 2020; Kima *et al.* 2020; Amole *et al.* 2021), but few were conducted on water productivity within a mixed-crop–livestock system across the three climatic zones of Burkina Faso (Sudan, Sudan–Sahel, and Sahel). Furthermore, limited information is available on both livestock and crop water productivity (LWP, CWP) within these zones and globally across West Africa. From this perspective, the study aimed to quantify CWP and LWP across the three climatic zones. At first instance, the study gave a brief description of crop–livestock farming households.

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[1] FAO: Food and Agriculture Organization.

Secondly, it addressed, the feeding strategies of livestock and crop and livestock outputs from the farming system; and finally, we quantify water depleted in the system, and water productivity of both crop and livestock.

While expecting variability in water productivity in mixed-crop–livestock systems under different climatic conditions, it is also expected that the findings give information on the needed actions to be undertaken in order to enhance the water productivity to the benefit of small farmers within a water-stressed region such as Burkina Faso and SSA in general.

2. STUDY METHODS

2.1. Study area

The study was carried out in three districts (Dori, Niou, and Dano) located in the Sahel, Sudan–Sahel, and Sudan zones, respectively. Dori district is located between latitudes 14° and 15° North and longitudes 0° and 3° West. Niou district lies between between latitudes 12° and 13° North and longitudes 1° and 2° West, and Dano is between latitudes 11° and 12 ° North and longitudes 3° and 4° West (Figure 1). The main socio-economic activities of the study zones include livestock and crop farming with some differences when we move from the Sahel to Sudan zone. The Sahel zone is more specialized in livestock breeding than cropping, whereas the Sudan zone distinguished itself with more suitable climatic conditions allowing farmers to practice more crop farming. The Sudan–Sahel is the transition zone where farmers combine the two activities in their production system.

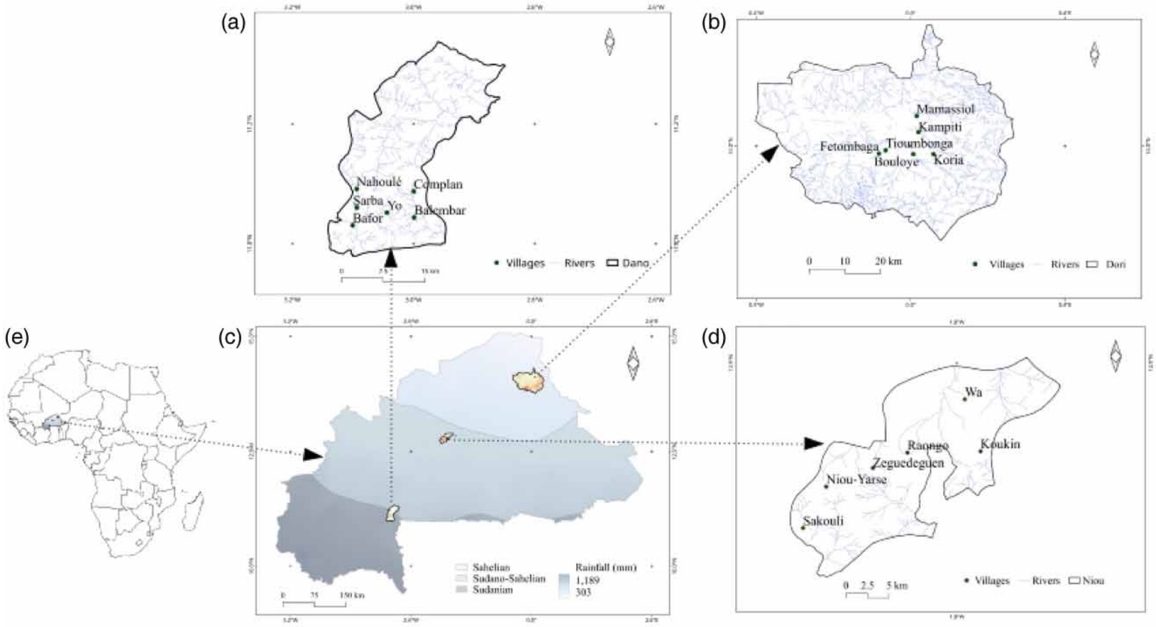

Figure 1 | Location of study areas across the three climatic zones of Burkina Faso (West Africa): (a) Dano district; (b) Dori district; (c) Map of Burkina Faso; (d) Niou district; (e) Map of Africa.

2.2. Data collection

Crop and LWP required major data sets including household land holding, crop type cultivated and land use, livestock feed sources, grazing lands, and other socio-economic information. Data also included: (i) livestock holding and herd composition, (ii) crop yield per crop type, (iii) livestock productions (milk, sales of live animals as flock offtake), and services (transport, draft power, and manure). These data were both collected empirically and through secondary data. Primary data were generated through interviews, field observations, and discussions with key informants. The collected information on crop and livestock production covers a period of 12 months given the inability of farmers to give detailed and reliable information beyond a period of one year.

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

Crop-livestock integration activities in practice in the village. Also, a purposely random sampling was done to select a set of six villages in each municipality where at least 30 individual farmers were interviewed about the crop–livestock farming systems. The total population involved in the study was 589 households made up of 195, 203, and 191 households in the Dano, Niou, and Dori municipalities, respectively.

The level of precision corresponding to the size of this sample is 4.03%. It is computed based on the following formula of Dagnelie (1998):

$$\delta = Z_{1-\alpha}\sqrt{\frac{p(1-p)}{n}} \tag{1}$$

where Z is the value of the normal random variable (1.96 for $\alpha = 0.05$); in other words, Z allows the determination of the corresponding deviation for the student's law distribution; its value is 1.96 when the accepted confidence threshold is 95%. p is the proportion of respondents who performed crop–livestock integration practices. n is the estimated sample size and δ the predetermined margin of error for the survey (4.03%).

2.3. Data analysis

2.3.1. Farming households across climatic zones

Farming households were studied by analyzing their structural and functional characteristics assessed through (i) their size and workforce they possess; (ii) their cultivated areas; (iii) the age of household heads; (iv) their major farming equipment; and (v) their herd ownership.

2.3.2. Crop and LWP

Water productivity is a function of the depleted water (representing the amount of water that is lost through ET) and the beneficial outputs from crops and livestock (Peden *et al.* 2007). Indeed, CWP consists of 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, LWP is the ratio of net livestock-related benefits, including both products and services, to the water depleted and degraded in producing these products (Gebreselassie *et al.* 2009; Haileslassie *et al.* 2009a, 2009b).

CWP and LWP were computed using Equations (2) and (3):

$$\mathrm{CWP} = \frac{C_j P_j}{(\mathrm{ET_o} K_{cj} \beta_j)} \tag{2}$$

where CWP is the crop water productivity of crop type j at the household level; C_j is the yield of crop type j (kg); P_j is the market value of crop j (US\$/kg); β_j (m^2) is the land area under crop j; $\mathrm{ET_o}$ (mm) is the reference evapotranspiration; K_{cj} is coefficient of crop type j obtained from the FAO database (Smith 2000). K_c consisted of the mean value of different growth stage crop coefficients (FAO 1998). Its value here also considered the length of the growing period.

$$\mathrm{LWP}_i = \frac{\sum (O_i P_i + S_i P_i)}{\sum \mathrm{WD}_k} \tag{3}$$

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

2.3.3. Depleted water estimation in mixed-crop–livestock farming

The estimation of the depleted water in crop and livestock production was a function of water lost through ET during production processes. The computation of ET used crop coefficient (K_c) for different stages of development for each crop type using Equation (4) (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 on the growing periods found in the literature was cross-checked by the state extension services in charge of agriculture in the study zones.

$$\mathrm{ET}_{ci} = \sum (\mathrm{ET_o} K_{ci} \mathrm{LGP}_i) \tag{4}$$

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; $\mathrm{ET_o}$ is the average reference evapotranspiration (mm/d); K_{ci} is the 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 ($\mathrm{ET_o}$) 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 (5) (Haileslassie *et al.* 2009b):

$$\mathrm{WD}_{cj} = \sum (\mathrm{ET}_{cij} \mathrm{HI}_{ij} \beta_{ij}) \tag{5}$$

where WD_{cj} is the total water depleted for crop i grain production in household j; ET_{cij} is the evapotranspiration for crop i in household j (mm); β_{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 ($\mathrm{WD_{CR}}$) production is estimated using Equation (6):

$$\mathrm{WD}_{\mathrm{CR}_j} = \sum (\mathrm{ET}_{cij}(1 - \mathrm{HI}_{ij})\mathrm{CR}_{ij}\beta_{ij}) \tag{6}$$

where $\mathrm{WD_{CR}}$ is the water depleted for crop i residues in household j (mm); ET_{cij} is the evapotranspiration for crop i in household j (mm); β_{ij} is the growing area of crop i types in household j (m^2); CR_{ij} is the utilization factor of the crop residue of crop i for household j (fraction).

Water depleted for communal grazing lands is estimated using Equation (7):

$$\mathrm{WD}_{GLj} = 10\mathrm{ET}_{c,\,gr}\mathrm{GL}_j\mathrm{FU_{GL}} \tag{7}$$

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

2.3.3.1. Assumptions and Secondary Data Sourcing.

Following assumptions were made in the 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.* 2009a). This was done assuming equal access to feed available from communal grazing areas per household (Amole *et al.* 2021). A total livestock density of 0.2TLU/ha was considered to be an average livestock density for Sahel and Sudan–Sahel zones, while 0.4TLU/ha was considered to be an 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 by livestock during the wet and dry seasons for grazing lands in similar agro-ecological conditions (Amole *et al.* 2021).

2.3.4. Estimation of crops beneficial outputs

Information on 2020/2021 average yields (kg/ha/year) for the major crops cultivated in each studied zone were obtained from the heads of farming household. 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).

2.3.5. Estimation of livestock beneficial outputs and services

Livestock beneficial outputs were products (milk, meat, and 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 donkeys 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 was used for cattle, sheep, and goats, respectively (Fofana *et al.* 2011). 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.* 2012; 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.* 2012). 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; 50 kg bag of urea, and 50 kg bag of phosphate). 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 (Table S1).

(iii) Offtake rate and meat value: the estimation was done based on the offtake rate assuming carcass weight of 52% for bovines and 46% for 'shoats' (sheep and goats) (FAO 1999) and the age of maturity was taken as five years, 5.5 years, and 1.5 years for cattle, donkey, and goat/sheep, respectively (Houenou *et al.* 2012). To avoid an overestimation of LWP (given that yearly water depleted to produce feed cannot solely account for the carcass weight) and ensure that 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, and household waste) 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 & Chilonda 2002).

2.3.6. Statistical analysis

Data from the survey and relevant secondary data were organized, summarized, and analyzed using R Software, a language and environment for statistical computing and cited in the manuscript (R Core Team 2022). Data were statistically checked for meeting the assumptions of normality (Shapiro-Wilk test) and variance homogeneity (Levene test). Barplots were built to visualize water productivity across the three climatic zones. To compare the obtained results between the three climatic zones, we performed a one-way analysis of variance (AVOVA). The Tukey's Honest Significant Difference (Tukey HSD) analysis (Tukey 1949) was afterwards performed when significant differences were detected. Alternative non-parametric tests (Kruskal–Wallis and Pairwise Wilcoxon Rank Sum Tests) were carried out when the assumptions of normality and equality of variance of data were not met.

3. RESULTS AND DISCUSSION

3.1. Household characteristics

Sedentary-extensive farmers were interviewed and were characterized based on different factors such as by the age of the household head, the available workforce, the number of members, the residence status, the marital status, the gender, and the ethnic group. Farmers' age and their workforce did not differ significantly between the Sudan (45 ± 11 years and 6 ± 4 workers) and Sahel (47 ± 13 years and 5 ± 3 workers) zones but they differed significantly from those of the Sudan–Sahel zone that distinguished itself by older farmers (49 ± 11 years) and the available workforce (6 ± 3 workers) ($p < 0.05$) (Table 1). Household size was significantly different from the Sudan zone (10 ± 6 persons) through the Sudan–Sahel (13 ± 6 persons) to the Sahel zone (11 ± 5 persons). The majority of interviewed households are native to each study site (186, 201, and 191 in Dano, Niou, and Dori, respectively) and the majority are married (193, 198, and 184 in Dano, Niou, and Dori, respectively). Households' heads are male in general and the main ethnic groups are Dagara (190), Mossi (200), and Fulani (191) as we move from Dano to Dori (Table 1).

Table 1 | Household characteristics

Integration variables		Sudan (Dano)	Sudan–Sahel (Niou)	Sahel (Dori)
Household head age (year)		$45 \pm 11^{a**}$	$49 \pm 11^{b**}$	$47 \pm 13^{a**}$
Workforce (worker)		$6 \pm 4^{a*}$	$6 \pm 3^{b*}$	$5 \pm 3^{a*}$
Household size (person)		$10 \pm 6^{a**}$	$13 \pm 6^{b**}$	$11 \pm 5^{c**}$
Residence status	Native	186^{a*}	201^{b*}	191^{c*}
	Non-native	9^{a*}	2^{b*}	0^{c*}
Marital status	Married	193^{a*}	198^{b*}	184^{c*}
	Single/Widow	2^{a*}	5^{b*}	7^{c*}
Gender	Male	194^{a*}	200^{b*}	180^{c*}
	Female	1^{a*}	3^{b*}	1^{a*}
Ethnic group	Dagara	190^{a*}	1^{b*}	0^{c*}
	Mossi	2^{a*}	200^{b*}	0^{c*}
	Fulani	3^{a*}	2^{b*}	191^{c*}

Mean ±SD with different superscripts along the lines differ significantly. Significant codes: 0 '***'; 0.001 '**'; 0.01 '*'; 0.05 '.'; 0.1 ' '; 1.

Farm size differed significantly between climatic zones and was comparatively bigger (5.7 ± 4.1 ha) in the Sudan zone compared to the Sudan–Sahel (4.2 ± 2.2 ha) and Sahel zone (3.9 ± 2.4 ha) ($p < 0.05$). Herd size (4.8 ± 4.6 TLU for ruminants, 5.5 ± 4.7 for swine, 2.0 ± 1.0 for donkey) was similarly bigger in the Sudan zone. The Sahel (2.8 ± 2.7 TLU) and Sudan–Sahel (2.4 ± 2.4 TLU) zones had similar ruminant herd sizes that differed significantly from that of the Sudan zone ($P < 0.05$). Herd size obtained for sedentary-extensive farmers in Niou (Sudan–Sahel) is bigger than that obtained (1.9 TLU) in the same zone (Amole *et al.* 2021). However, these authors in the Sahel zone found a higher herd size (5.3 TLU) than that of the current study. Overall, farming equipment (cart, plough, hoe, and compost pit) was found significantly different between zones. Sudan and Sudan–Sahel zones seem to have more cropping equipment than the Sahel zone (Table 2). This confirms the nature of cropping-oriented farmers than livestock rearing-oriented farmers in these zones compared to the Sahel zone.

3.2. Crop and LWP

3.2.1. Contribution of different feed resources

Within each climatic zone, the animal feed was mainly crop residues, natural pasture, and agricultural by-products and their usage differs according to the seasons. Indeed, natural pastures constitute the main feed source (41–42, 27–33, and 59–75%) in Sudan (Dano), Sahel (Dori), and Sudan–Sahel (Niou) zones, respectively, for ruminant livestock (cattle, sheep, goat) in the wet season (Figure 2 and Supplementary material Figures S1 and S2). Crop residues (cereal straw, legume residues, and cowpea 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,

Table 2 | Characterization of mixed-crop–livestock system across the three climatic zones

Integration variables	Sudan (Dano)	Sudan–Sahel (Niou)	Sahel (Dori)
Farm size (ha)	$5.7 \pm 4.1^{a**}$	$4.2 \pm 2.2^{b**}$	$3.9 \pm 2.4^{c**}$
Ruminant (TLU)	$4.8 \pm 4.6^{a***}$	$2.4 \pm 2.4^{b***}$	$2.8 \pm 2.7^{b***}$
Donkey (nb)	$2.0 \pm 1.0^{a*}$	$2.0 \pm 2.0^{a*}$	$1.0 \pm 0.0^{b*}$
Swine (nb)	$5.5 \pm 4.7^{a**}$	$4.8 \pm 4.1^{b**}$	–
Cart (nb)	$< 1^{a*}$	$< 1^{b*}$	$< 1^{c*}$
Plough (nb)	$1 \pm 1^{a*}$	$1 \pm 1^{b*}$	–
Hoe (nb)	$9 \pm 8^{a**}$	$7 \pm 3^{b**}$	$4 \pm 2^{c**}$
Compost pit	$< 1^{a*}$	$< 1^{a*}$	–

Mean ±SD with different superscripts along the lines differ significantly. Significant codes: 0 '***'; 0.001 '**'; 0.01 '*'; 0.05 '.'; 0.1 ' '; 1.
nb, number; <, less than.

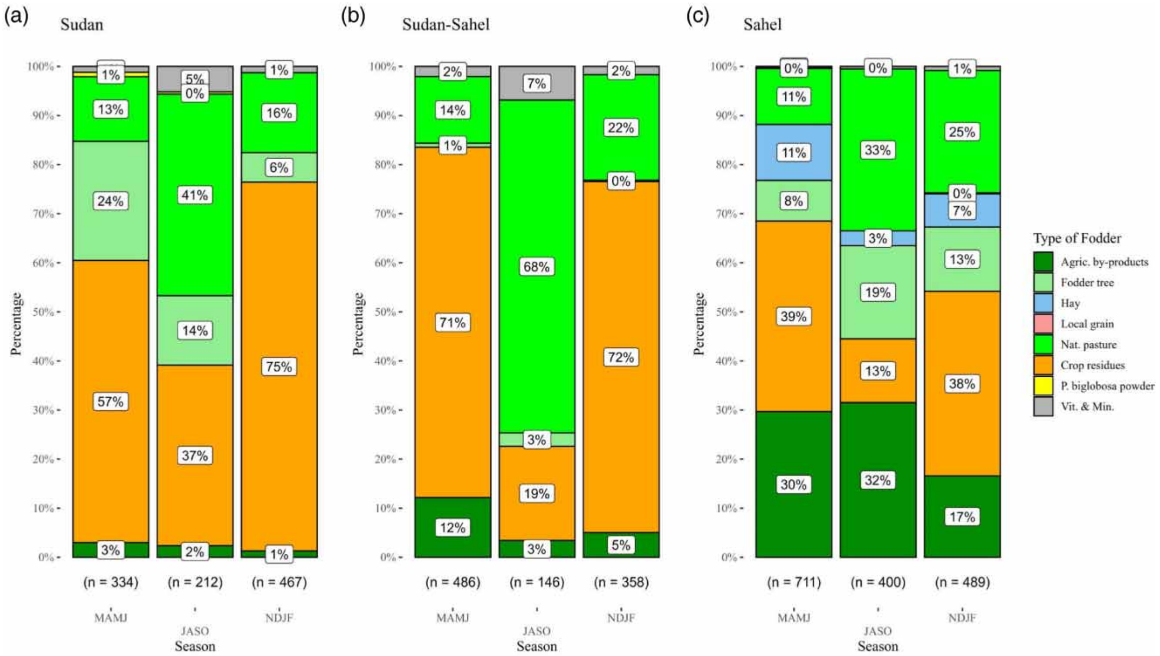

Figure 2 | Feed sources available for cattle feeding across seasons and climatic zones of Burkina Faso: (a) Sudan zone, (b) Sudan-Sahel zone and (c) Sahel zone. MAMJ: March-April-May-June; JASO: July-August-September-October; NDJF: November-December-January-February.

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 also important feed sources across the seasons (Figure 2, SM2 and SM3). Therefore, the feeding strategies of ruminants across climatic zones rely essentially 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 were 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 residue biomass produced by farming systems. In such conditions, farmers must rely additionally on agricultural by-products (bran, grain, and cotton seed cake) 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 & Ayantunde 2019). Different feed sources sustain livestock production (meat, milk, and manure) and services, across climatic zones that are facing challenges of suitable herd feeding.

3.2.2. Livestock and crop beneficial outputs

The dominant livestock species in the study zones include cattle (*Bos indicus and Bos taurus*), sheep (*Ovis aries*), goats (*Capra hircus*), and donkey (*Equus asinus*). They serve multiple purposes such as the source of milk, meat, and draft power. The dominant crop species grown across zones are sorghum (*Sorghum bicolor*), millet (*Panicum sp.*), and maize (*Zea mays L.*) which constitute the main pillars of Burkina Faso's food security across West Africa (Waongo *et al.* 2015). Besides these cereal crops are groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) which play a dual role as staple and cash crop for vulnerable small-scale farmers in the zones.

Livestock beneficial output (US$/household.year^{-1}) included livestock offtake, livestock services (traction), milk, and manure produced, while crop beneficial outputs consisted grain yield.

Both physical and financial crop outputs per household per annum were higher (2,723.3 ± 158.5 kg/household/year and 1,140.5 ± 1,056.8US$/household/year) in the Sudan zone ($P < 0.05$) (Table 3). Livestock financial outputs were in the range of 710.2 ± 42.8–1,228.2 ± 83.7 US$/household/year. This compared well with 679.88 ± 756–1,436.1 ± 63.7 US$/household/year reported for mixed-crop–livestock farming in Ethiopia (Abebe 2012).

Table 3 | Crop–livestock beneficial outputs per household (US$/household/year) 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^{a***}
Sudan–Sahel (Niou)	1,406.0 ± 59.5^{b***}	606.7 ± 27.1^{b***}	820.5 ± 39.8^{b***}	1,429.8 ± 56.4^{b***}
Sahel (Dori)	1,779.4 ± 80.7^{c***}	825.8 ± 37.1^{c***}	710.2 ± 42.8^{c***}	1,532.9 ± 68.2^{c***}

Mean ±SD error with different superscripts along the column differ significantly. Significant codes: 0 '***'; 0.001 '**'; 0.01 '*'; 0.05 '.'; 0.1 ' '; 1.

The quantity and value of milk produced (160.3 ± 13.5 l/TLU/year and 136.8 ± 122.8 US$/household/year) in the Sahel zone were the highest ($P < 0.05$) (Table 4). Values for manure (187.21 ± 172.06 US$/household/year), livestock services (285.2 ± 220.5 US$/household/year), and quantity and value of meat (333.1 ± 213.3 kg/household/year and 752.8 ± 672.9 US$/household/year) from the Sudan zone were higher ($P < 0.05$) than those from Sudan–Sahel and Sahel zones (Table 4). 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$/household/year), livestock offtake (136.2 US$/household/year), manure (1.8 US$/household/year), and services (1.2 US$/household/year). Similarly, for the Sudan–Sahel zone, Amole *et al.* (2021) reported lower values for livestock offtake (98.2 US$/household/year), manure (2.1 US $/household/year), services (25.6 US$/household/year).

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 5).

3.2.3 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/year and was higher ($p<0.05$) in the Sahel zone (Figure 3). The depleted water for livestock feed production varied from 1,748.9 ± 945.0 to 2,852.4 ± 798.9 m^3/ha/year and was also higher in the Sahel ($p<0.05$). This situation could be explained by the high evaporation potential that characterizes the Sudan–Sahel and Sahel zones compared to the Sudan zone. The amounts of water depleted for feed production were similar to those indicated by Amole *et al.* (2021), in the Sahel (2,888.71 m^3/ha/year) and Sudan–Sahel (2,777.18 m^3/ha/year) regions.

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

Table 4 | Crop and livestock beneficial output values in the study sites

Zones	Services (US$/household/year)	Manure (US$/household/year)	Milk (l/TLU/year)	Milk (US$/household/year)	Meat (kg/household/year)	Meat (US$/household/year)
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***}

Mean ±SD error with different superscripts along the column differ significantly. Significant codes: 0 '***'; 0.001 '**'; 0.01 '*'; 0.05 '.'; 0.1 ' '; 1. For manure, fertilizer values of N, P, and K are considered.

Table 5 | Potential fertilization 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***}

Mean ±SD error with different superscripts along the column differ significantly. Significant codes: 0 '***'; 0.001 '**'; 0.01 '*'; 0.05 '.'; 0.1 ' '; 1.

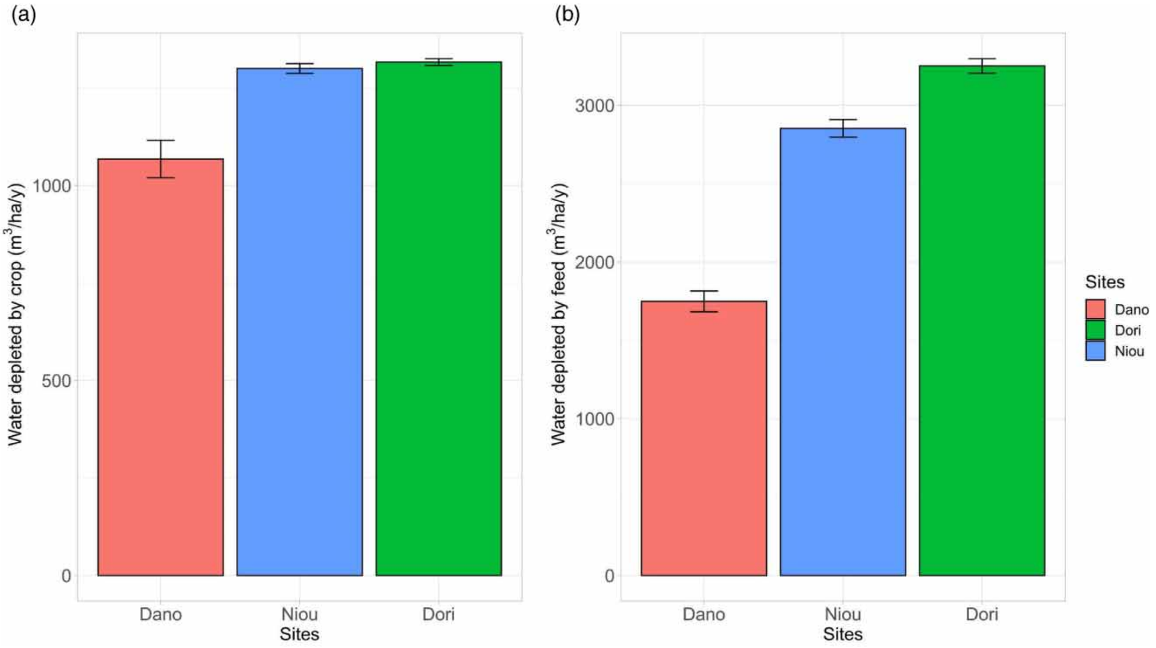

Figure 3 | Water depleted (m^3/ha/year) by crop (a) and livestock feed (b) productions across climatic zones.

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

3.2.4. Crop–LWP

With higher returns from the crop–livestock beneficial output, physical CWP (0.40 $\pm$0.02 kg/m^3) and financial LWP (0.17 $\pm$ 0.01 US$/m^3) were the highest in the Sudan zone ($p < 0.05$). Likewise, the highest total water productivity (TWP) (0.29 $\pm$ 0.01 US$/m^3) was experienced in this zone ($p < 0.05$). However, despite the highest return of crop output in Sudan, the highest financial CWP (0.16 $\pm$ 0.01 US$/m^3) was experienced in the Sahel zone. It differed significantly from that of Sudan (0.15 $\pm$ 0.01US$/m^3) and Sudan–Sahel (0.13 $\pm$ 0.01 US$/m^3) zones (Figure 4). Lower values of LWP were experienced in the Sudan–Sahel (0.09 $\pm$ 0.01 US$/m^3) and Sahel (0.06 $\pm$ 0.01US$/m^3) zones. Similarly, lower physical CWP was experienced within Sudan–Sahel (0.29 $\pm$0.01 kg /m^3) and Sahel (0.33 $\pm$0.01 kg/m^3) zones (Figure 4).

The findings on crop–LWP compared well with those of previous literature. Indeed, LWP experienced across climatic zones revealed an increasing trend (0.06 $\pm$0.01 US$/m^3 to 0.17$\pm$0.01 US$/m^3) from the Sahel to the Sudan zone. These values in the Sudan–Sahel and Sahel zones were similar to those of 0.06–0.08 US$/m^3 reported by Mekonnen *et al.* (2011) in Ethiopia and 0.01–0.11 US$/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$\pm$0.01US$/m^3) was quite similar to the average value (0.16 $\pm$0.01 US$/m^3) indicated by Abebe (2012) and within the range (0.1 and 0.6 US$/m^3) indicated by Haileslassie *et al.* (2009a) and Haileslassie *et al.* (2009b) in Ethiopia.

Financial CWP (0.13 $\pm$0.01 to 0.16$\pm$0.01US$/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 $\pm$0.01 to 0.40$\pm$0.02 kg/m^3) across climatic zones was quite similar to the findings

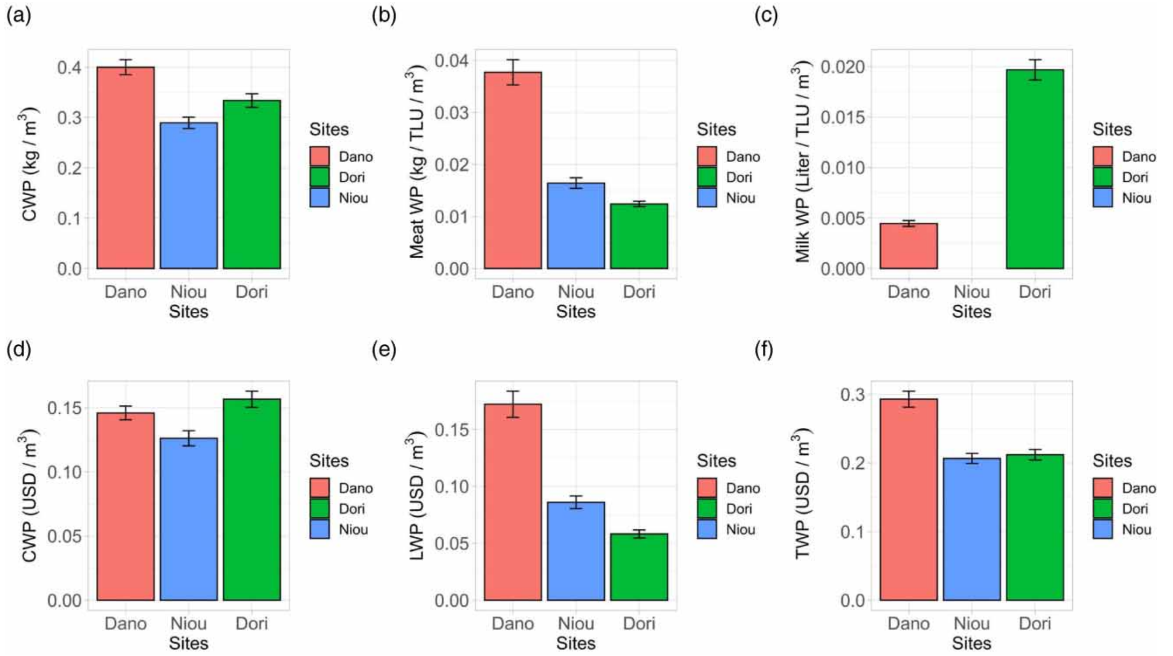

Figure 4 | Crop-livestock physical ($kg/m^3 \pm$ sd error) and financial ($US\$/m^3 \pm$ sd error) water productivity across climatic zones of Burkina Faso. (a) and (d) CWP: Crop Water Productivity (kg/m^3 or USD/m^3), (b) Meat WP: Meat Water Productivity ($kg/TLU/m^3$), (c) Milk WP: Milk Water Productivity ($Liter/TLU/m^3$), (e) LWP : Livestock Water Productivity (USD/m^3), (f) TWP: Total Water Productivity (USD/m^3). TLU: Tropical Livestock Unit.

0.24–0.38 kg/m^3 by Haileslassie *et al.* (2009b) and 0.3–0.5 kg/m^3 by Haileslassie *et al.* (2009a). Kima *et al.* (2020) and Bama *et al.* (2020), respectively, reported higher CWP values of 0.41 and 0.85 kg/m^3 within rice-based systems in Burkina Faso. There are possibilities to improve CWP 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 to 0.02 ± 0.01 L/m^3 within the Sudan and Sahel zones, respectively. Meat water productivity amounted to 0.04 ± 0.03 kg/m^3 in the Sudan zone, 0.02 ± 0.01 kg/m^3 in the Sudan–Sahel zone, and 0.01 ± 0.01 kg/m^3 in the Sahel zone (Figure 4). 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.

4. CONCLUSION

Feeding strategies of livestock within the Sudan zone differed globally from those of Sudan–Sahel and Sahel zones. Crop residues are generally available to livestock throughout the year in the Sudan zone, unlike the two other zones. However, crop residues occupied a more central role in feeding strategies of livestock in Sudan–Sahel especially during the hot and dry season. The feeding strategies of the Sahel zone relied mainly both on crop residues and agricultural by-products. Across all the zones, livestock feeding relied mainly on natural pasture during the rainy season and this was more pronounced in the Sudan–Sahel zone. Cropping and livestock feeding implies depleting water to produce meat, milk, cereals, and other crop products within all the zones. Crop and livestock production and the amount of water depleted to sustain such productions within each climatic zone differed significantly across climatic zones. Generally, the highest crop and LWP was experienced by farmers in the Sudan zone compared with the Sudan–Sahel and Sahel zones which are characterized by a harsher environment with comparatively less rain and higher temperature and ET.

The current level of crop and LWP can be improved through adequate actions aiming to enhance both livestock and crop beneficial outputs across the climatic zones of Burkina Faso. The improvement could also be done through increased livestock feeding of high-quality crop residues collected and stored in good conditions that prevent the deterioration of their nutritional quality. Additionally, *in-situ* field water harvesting techniques such as *demi lunes* (half-moons) and *Zaï* can improve the quantity and quality of crop residues.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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