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Heliyon 10 (2024) e28748

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Integrated crop-livestock effects on soil carbon sequestration in Benin, West Africa

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ARTICLE INFO

Keywords:
Climate change
soil carbon sequestration
Agricultural practices
Livestock
Mitigation
Benin

ABSTRACT

In Benin, adaptation to climate change in the livestock sector has led cattle farmers to develop different livestock practices. Most research has focused on evaluating the effects of these practices on livestock productivity. However, information on the effect of these practices on carbon (C) sequestration in farmland soils is lacking. Soil C sequestration has been identified as a potential strategy to offset greenhouse gas emissions. Thus, the present study aimed at filling this gap. The calculation was one hand based on inventory data obtained from literature sources (excrement production of each cattle category, moisture content of each crop, ratio of crop residue to main product, and C content of the main product and excrement) and on the other hand on activity data (cattle herd size, manure applied, land use area, crop yield, and crop residues management) obtained from surveys carried out among 360 cattle farmers belonging to 3 cattle farming types. The results revealed that whatever the cattle farming type, annual C input from manure was higher ($p<0.05$) than C input from crop residues. Annual C sequestration in farmland soil of farms integrating livestock with cereal-legume and forage crops was significantly higher (Type 2: 158.07 ± 1.79 kg C ha^{-1} $year^{-1}$) followed by farms integrating livestock with cereal-legume crops (Type 1: 99.51 ± 0.95 kg C ha^{-1} $year^{-1}$), which in turn had a higher value than farms practicing pastoral mobility (Type 3: 78.46 ± 0.70 kg C ha^{-1} $year^{-1}$). These results highlight the potential for climate change mitigation through these farming practices. This is justified because the quantity of C sequestered in farmland soil of all cattle farming types was significant. Thus, for future research, it is necessary to include soil C sequestration in the calculations of farms' carbon footprint.

1. Introduction

The global warming of the planet is now unequivocal. The impacts of extreme climatic events that have occurred in recent years bear witness to this [1]. These impacts emphasis great vulnerability and high degree of exposure of ecosystems and human societies to climate variations [2]. Moreover, these climate changes raise fears of major disruptions for societies in their relations with their environment, and may even threaten the ecosystem services from which they benefit directly or indirectly [3]. The excessive

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https://doi.org/10.1016/j.heliyon.2024.e28748
Received 19 June 2023; Received in revised form 18 March 2024; Accepted 24 March 2024
Available online 25 March 2024

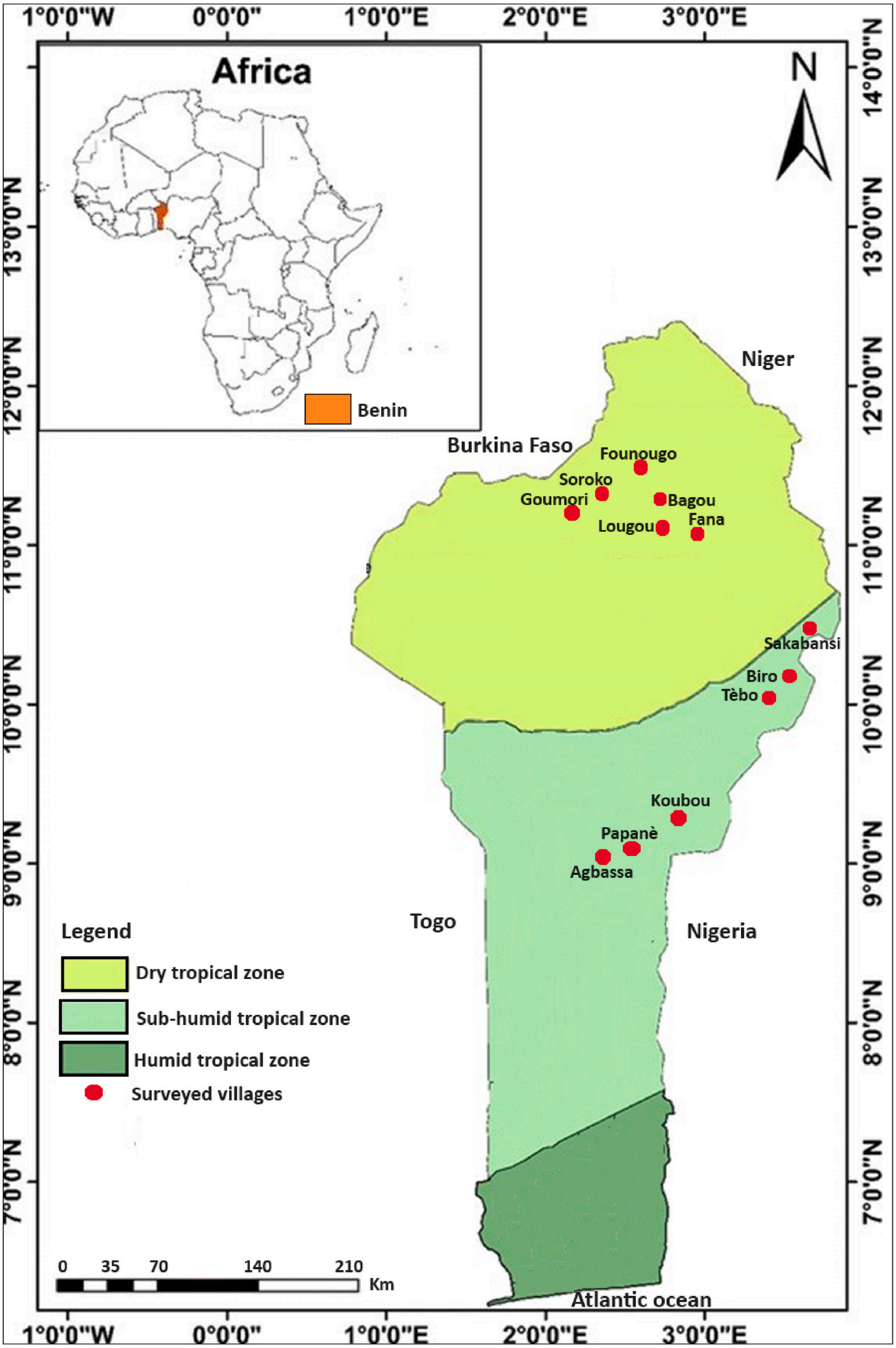

Fig. 1. Map showing the selected zones and the location of the villages surveyed in Benin.

combustion of fossil fuels, agriculture, livestock, and land use changes are part of human activities that contribute significantly to global warming [3]. Climate change represents a major challenge for the future and many studies have been carried out to assess the impact of different activities of the various sectors on the climate [4].

The livestock sector contributes to 14.5% of all anthropogenic greenhouse gas (GHG) emissions [5]. They are mainly due to ruminants, with 65% attributed to dairy and beef bovines and 6.5% to small ruminants. However, ruminant grazing systems would “only” be responsible for 20% of total emissions from livestock [5,6]. The main emission sources are enteric fermentation, feed production, and manure management [5]. For GHG emissions, large disparities exist between the regions of the world. In terms of total emissions, sub-Saharan Africa accounts for a fairly limited proportion (4%) [7]. However, its farming systems, have the highest GHG emissions per unit of product compared to other regions of the world. This is mainly attributed to low animal productivity and low quality of feeds [8]. GHG emissions from livestock systems in sub-Saharan Africa could be offset by carbon storage in the ecosystems in which these livestock systems are practiced [9]. Due to the photosynthetic activity of plants, the presence of vegetation on the ground promotes the long-term absorption of CO_2 from the atmosphere [10]. Several studies have shown that the storage of C in the soil depends on farming practices and the mode of land use [11,12].

In sub-Saharan Africa, several practices are implemented by cattle farmers to manage the herd [13,14]. In Benin, Idrissou et al. [15] identified three cattle farming types according to their practices. This involves: integrating livestock with cereal-legume crops cultivation (Type 1); integrating livestock with cereal-legume and forage crops (Type 2), and pastoral mobility (Type 3). The main difference between the first two cattle farming types is that farmers type 2 abandon or reduce the area of some cereal-legume crops in favor of forage crops. In addition, their production goal is to produce and sell milk which is not the case with farmers type 1. Out of the fact that these practices are herd management practices, they are nowadays adaptation strategies for cattle farmers to against climate change [16]. This is justified by the fact that cattle farmers have made several modifications or changes to these old practices to adapt to the impact of climate change that they have observed on their livelihoods. These impacts were the decline in the production and quality of fodder, the reduction in the growth and reproduction performance of animals, and the decline in milk production [17]. Most research has focused on evaluating the effects of these practices on livestock productivity [15,18,19]. However, information on the effect of these practices in farmland soil C sequestration is lacking. This information is necessary because it will allow us to identify practices that are climate change mitigation measures. Another innovative aspect of this study is that it will provide data on the farmland soil C sequestration which will be used in the calculations of the C footprint of these farms. Several studies evaluate the C footprint of livestock farms without taking into account the amount of soil C sequestered by its farms [6]. This could lead to bias results.

In sub-Saharan livestock farming context, some studies have assessed soil C sequestration in transhumant livestock systems [9]. However, these are not the only livestock farming systems encountered in Africa. Nowadays, sedentary systems are becoming numerous [13]. It would therefore be appropriate to consider them in such studies. Moreover, within the same livestock farming system, the practices of farmers may vary, with potential impact in farmland soil C sequestration. The three cattle farming types identified by Idrissou et al. [15] illustrate this situation well. The first two farming types with different practices belong to the sedentary system and the third type to the transhumant system.

According to literature, there are several approaches to assess farmland soil C sequestration: i) changes in C stocks according to inventories [20], and ii) three models based on net C fluxes in agricultural soils [21–23]. By comparing these different approaches, several studies [6,24] revealed that the approach proposed by Petersen et al. [23], based on real data on C inputs and a time perspective of 100 years for global warming potential, seems to give more precise and realistic results and allows to design mitigation strategies with best precision. Our study used this approach to estimate farmland soil C sequestration using survey data collected at the farm level.

The general aim of this study was to estimate the soil C sequestration in three cattle farming types in the dry and sub-humid tropical zones of Benin. Specifically, the study sought to: (i) quantify C input from manure and crop residues, and (ii) estimate the amount of C sequestered in farmland soil of three cattle farming types.

2. Material and methods

2.1. Study zones

This study was carried out in two of the three climatic zones of Benin: the dry tropical zone (DTZ) located between 9° 45′ and 12° 25′ N and the sub-humid tropical zone (STZ) located between 7° 30′ and 9° 45′ N (Fig. 1). The choice of these zones is based on climate forecasts which indicates that they are the most vulnerable places to rainfall deficit and high sunshine [25,26], yet more than 85% of the Beninese cattle herd is concentrated in these zones [27].

In each zone, two (2) municipalities were chosen based on a large number of cattle farmers and preliminary interviews with technicians from the “Agences Territoriale pour le Développement Agricole” (ATDA). Thus, the municipalities of Banikoara and Gogounou were in DTZ, and those of Tchaourou and Nikki were in STZ. Within each municipality, three (3) villages were selected based on their importance in cattle farming and accessibility (Fig. 1).

The DTZ has hydromorphic, well-drained soils, and lithosols. The vegetation of this zone is mainly composed of savannas with small trees [28]. The mean annual rainfall is 953 mm [29]. The temperature varies from 24 to 31 °C and relative humidity varies from 18 to 99% [28].

In STZ, soils are ferruginous with variable fertility [30,31]. The vegetation is characterized by a mosaic of woodland, dry dense forests, tree and shrub savannas, and gallery forests [28]. The mean annual rainfall is 1155 mm [29]. Annual temperature varies from 25 to 29 °C and relative humidity ranges from 31 to 98% [32].

2.2. Sampling

This work was carried out on the same sample (360 cattle farmers) as that used by Idrissou et al. [15] in Benin. These authors characterized 360 cattle farms according to their practices in the face of climate change. These results enabled to identify three cattle farming types according to their practice.

- Type 1: Cattle farming with the practice of integrating livestock with cereal-legume cultivation. Although this practice is old but, it is nowadays a strategy for adapting to climate change. This is justified through the changes made by the cattle farmers. These changes involved: growing new crop variety, growing drought tolerance crop variety, modification of cultivation techniques and agricultural calendar. This practice was developed mainly by 41.39% of the cattle farmers surveyed (i.e., 149 cattle farmers). These cattle farmers are sedentary, mainly located in the STZ where the mean annual rainfall is 1155 mm and annual temperature varies from 25 to 29 °C [29,32]. The production goal of these farmers was milk and meat. The size of their cattle herd is the smallest (24 heads). This cattle farming type's crop area is around 6.5 ha. During the rainy season, animal feed in this farming type is provided only by natural rangeland. During the dry season outside natural rangeland, animals receive crop residues (See Appendix).
- Type 2: Cattle farming with the practice of integrating livestock with cereal-legume and forage crops. To adapt to climate change, all cattle farmers of this type have abandoned or reduced the areas of some cereal-legume crops in favor of forage crops. This practice was developed by 69 cattle farmers, i.e., 19.17% of the total cattle farmers surveyed. These cattle farmers are also sedentary and located in the DTZ where the mean annual rainfall is 953 mm and annual temperature varies from 24 to 31 °C [28,29]. Their production goal is to produce and milk. The size of their cattle herd is on average 30 heads. In this cattle farming type, natural rangeland and forage crops provide animal feed during the rainy season (See Appendix). During the dry season, animal feed is however provided by natural rangeland, forage crops, and feed concentrates. The area allocated to cereal-legume crops was on average 2.6 ha while that intended for forage crops was 1.22 ha.
- Type 3: Cattle farming with the practice based on pastoral mobility. This practice is first and foremost a way of life among Fulani herders. Faced with the scarcity of resources due to climate change, this practice has undergone modifications (early departure in transhumance, long distance and long duration of transhumance). This practice was developed by 39.44% of the cattle farmers surveyed (i.e., 142 cattle farmers). These cattle farmers are located in the DTZ characterized by a mean annual rainfall of 953 mm and annual temperature varies from 24 to 31 °C [28,29]. Their goal is to produce meat and milk. Their cattle herd size was the highest (63 heads). Farmers of this type plow small areas (around 1.5 ha) to cultivate only cereals intended to feed their families. Animal feed is provided by natural rangeland throughout the year (See Appendix). Before moving for the transhumance, animals receive crop residues.

2.3. Data collection

To carry out this study, two types of data were collected: inventory and activity data. Inventory data are fixed values obtained from the literature while activity data are values obtained from surveys among cattle farmers. The following inventory and activity data (Tables 1 and 2) were used to calculate the C inputs from manure and crops described in equations (1)–(5) [33].

2.3.1. Inventory data

Inventory data used to estimate the C amount from cattle manure were: (i) excrement production of each cattle category (cows, bulls, heifers/sub-adult bulls and calves) and (ii) C content of excrement. The average annual amount of dry matter production and the C content of excrement of each cattle category are shown in Table 1.

Inventory data used to estimate the C amount of crops were: (i) moisture content of each crop, (ii) C content of the main product, and (iii) ratio of residue to the main product (Table 2). Land use (LU) types were classified into 6 categories: maize, sorghum, millet, soybean, groundnut, and forage crop (*Panicum maximum*).

2.3.2. Activity data

The activity data used to estimate the C amount in cattle excrement were: (i) the number of each cattle category, and (ii) the allocation of the produced manure to farmland.

The activity data used to estimate the C amount of crop were: (i) LU type area, (ii) yield of each LU, and (iii) proportion of crop residues remaining on the field. These activity data were obtained from surveys carried out among cattle farmers.

Table 1
Inventory data used to estimate the C amount from cattle manure.

Parameters	Cattle categories				Sources
	Cows	Bulls	Heifers/Subadult bulls	Calves	
Manure excreted (kg DM head^{-1} year^{-1})	920	1108	719	373	Braber et al. (2021) [34]
Carbon content (%)	42.38	42.38	42.38	42.38	Xin et al. (2018) [35]

Table 2
Inventory data used to estimate the C amount of crops.

Parameters	Land use types						Sources
	Maize	Sorghum	Millet	Soybean	Groundnut	Forage crop	
Moisture content (%)	14.5	7.13	12.12	6	11.5	26.75	Toléba et al. (2009) [36] Adéoti et al. (2017) [37] Atchadé et al. (2019) [38] Idrissou et al. (2020) [39]
C content (%)	45	45	45	45	45	45	Batalla et al. (2015) [6] Bolinder et al. (2007) [40]
Ratio of residue to the main product	0.67	0.64	0.50	0.6	0.51	0.15	Kimura et al. (2011) [33] Serraj et al. (2005) [41] Oikeh et al. (2007) [42] Guimbirke, (2012) [43] Tovihoudji et al. (2017) [44] Faki et al. (2021) [45]

2.4. Calculations scheme

The C input to farmland soil considered in this study were cattle manure and crop residues.

2.4.1. Estimation of C input from cattle manure

The amount of C contained in the manure of each cattle category (cows, bulls, heifers/sub-adult bulls and calves) was first determined. These amounts were then added to obtain the C quantity of the entire herd. The calculation for a given cattle category is shown by the following equation:

$$C_{manure} = N_{Cattle} * A_{manure\ excreted} * C_{content\ of\ cattle\ manure} \tag{1}$$

Where C_{manure}: Carbon in manure for each cattle category (t C year^{-1}); N_{cattle}: Number of cattle category (head); $A_{manure\ excreted}$: Amount of manure excreted of each cattle category (t DM head^{-1} year^{-1}); $C_{content\ of\ cattle\ manure}$: Carbon content of cattle manure (%)

The allocation of manure to farmland was obtained from surveys carried out among cattle farmers. The amount of C contained in the manure applied was computed as follows:

$$C_{manure\ appli} = A_{manue\ appli} * C_{content\ of\ cattle\ manure} \tag{2}$$

Where $C_{manure\ appli}$: Carbon in manure applied (t C ha^{-1}year^{-1}); $A_{manure\ appli}$: Amount of manure applied to farmland (t DM ha^{-1} year^{-1}); $C_{content\ of\ cattle\ manure}$: Carbon content of cattle manure (%)

2.4.2. Estimation of C input from crop residues

The amount of C in crop was estimated for the six (6) land use types (maize, sorghum, millet, soybean, groundnut and forage crop). The amount of C in the harvest (main product) for each LU type was estimated as follows:

$$C_{main\ product} = A_{main\ product} * [(100 - moisture\ content\ ) / 100] * C_c \tag{3}$$

Where $C_{main\ product}$: Carbon in main product (t C ha^{-1} year^{-1}); $A_{main\ product}$: Amount of main product of each land use type (t FW ha^{-1} year^{-1}); C_C: Carbon content of main product (%)

By definition, crop residue is the part of the crop not harvested as product (including roots). The total C in crop residues for a given LU type was estimated from the ratio of residue to the main product (Equation (4)). The amount of residue remaining on the field was based on surveys carried out among cattle farmers, who provided information relating to the proportion of crop residue remaining on the field and removed from farmland for other uses (use as feed, domestic energy, roofing, and fencing materials). The amount of C in residue remaining on the field was calculated by multiplying the total C in crop residues by the proportion of crop residue remaining on the field (Equation (5)).

$$C_{residu} = C_{main\ product} * R_{res} \tag{4}$$

$$C_{residu\ rem} = C_{residu} * P_i \tag{5}$$

Where C_{residu}: Carbon in residue (t C ha^{-1} year^{-1}); $C_{main\ product}$: Carbon in main product (t C ha^{-1} year^{-1}); $C_{residu\ rem}$: Carbon in residue *remaining on the field (t C ha^{-1} year^{-1}); R_{res}: Ratio of* residue *to the main product; P_i: proportion of crop residues remaining on the field.*

2.4.3. Estimation of soil carbon sequestration

To estimate the quantity of C sequestered in the farmland soil, this study was based on the approach proposed by Petersen et al. [23]. This approach was designed to estimate the soil C changes as a consequence of the C input from crop residues and manure added to the soil. This approach was based on the modeling of two C fluxes: i) from the soil to the atmosphere, where the soil organic matter mineralization was modeled using the soil C model C-TOOL; ii) from the atmosphere to the soil, where the atmospheric CO_2 decay was modeled using the Bern Carbon Cycle model. Petersen et al. [23] observed that 10% of C added to the soil as organic C input would be sequestered in a 100-year perspective. To estimate soil carbon sequestration in this study, the same coefficient (10%) was applied to the amount of C input applied to farmland soil, consisting of: i) C contained in manure applied to farmland and ii) C derived from crop residues remaining on the field.

2.5. Statistical analysis

The survey data was entered into Excel 2010 software and imported into R.3.5.1 software [46] for statistical analyses. The data were subjected to one-way ANOVA to test for possible significant differences between the three cattle farming types. The multiple means were compared with the Tukey test when the ANOVA model indicated a significant difference ($p < 0.05$) between cattle farming types. Results were presented as the mean ± standard error.

3. Results

3.1. Farms characteristics

Table 3 shows the characteristics of the three cattle farming types. Type 1 farms had the highest cattle herd size (63 ± 0.32 heads), followed by farms type 2 (30 ± 0.24 heads). In farms type 3 the cattle size was lower (24 ± 0.27 heads).

In general, three categories of crops were encountered in the cattle farming types: cereal crops (maize, sorghum and millet), legume crops (soybean and groundnut) and forage crops (*Panicum maximum*). Cereal crops were common to all cattle farming types while legumes were only grown in types 1 and 2. Moreover, type 2 farms were the only ones that produced forage crops. The total crop area was higher in farms type 1 (6.35 ± 0.04 ha) followed by farms type 2 (3.36 ± 0.60 ha). Type 3 farms had the smallest crop area (1.45 ± 0.02 ha).

3.2. Manure production and application

Annual manure production and application are summarized in Table 4. The amount of manure produced per year varied ($p<0.05$) from one cattle farming type to another. The highest manure production was observed in farms type 3 (47.03 ± 0.26 t DM year^{-1}), while the lowest production was recorded in farms type 1 (18.22 ± 0.20 t DM year^{-1}). The amount of manure applied per unit area of farmland also varied ($p<0.05$) between cattle farming types. Thus, farms type 2 applied 2.89 t DM ha^{-1} year^{-1}, while farms type 1 and type 3 applied 2 t DM ha^{-1} year^{-1} and 1.72 t DM ha^{-1} year^{-1} respectively.

3.3. Crop residues production

3.3.1. Crop residues management

Crop residue management practices have been grouped into three categories (Table 5): use as feed, remaining on the field (as mulch or incorporated), and used for other purposes (use as domestic energy, roofing and fencing materials). Only cereal crop residues (maize, sorghum, and millet) were used as domestic energy, roofing and fencing materials.

In general, regardless of the cattle farming type, crop residues were valued much more in livestock feed (varied between 65 and 93%). The proportions of crop residues remaining on the field, which were the C input from crop residue, varied between 5 and 100%.

Table 3
Characteristics of cattle farming types.

Parameters	Type 1	Type 2	Type 3
Cattle herd			
Cows (heads)	9 ± 0.10^{c}	13 ± 0.12^{b}	30 ± 0.16^{a}
Bulls (heads)	2 ± 0.02^{a}	1 ± 0.03^{a}	2 ± 0.03^{a}
Heifers/Subadult bulls (heads)	8 ± 0.11^{c}	10 ± 0.12^{b}	18 ± 0.09^{a}
Calves (heads)	5 ± 0.07^{b}	6 ± 0.06^{b}	13 ± 0.07^{a}
Total herd size (heads)	24 ± 0.27^{c}	30 ± 0.24^{b}	63 ± 0.32^{a}
Crop area			
Maize (ha)	2.51 ± 0.05^{a}	1.15 ± 0.04^{b}	0.56 ± 0.03^{c}
Sorghum (ha)	2.06 ± 0.06^{a}	0.98 ± 0.05^{b}	0.48 ± 0.03^{c}
Millet (ha)	–	–	0.88 ± 0.01
Soybean (ha)	1.09 ± 0.03^{a}	0.52 ± 0.05^{b}	–
Groundnut (ha)	0.90 ± 0.02	–	–
Forage crop (ha)	–	1.22 ± 0.05	–
Total crop area (ha)	6.35 ± 0.04^{a}	3.36 ± 0.06^{b}	1.45 ± 0.02^{c}

a,b,c: Means with different letters on the same line differ significantly ($p < 0.05$).

Table 4
Manure production and application.

Parameters	Type 1	Type 2	Type 3
Manure production per *year*			
Cows (t DM $year^{-1}$)	8.72 ± 0.09^c	12.65 ± 0.11^b	27.83 ± 0.15^a
Bulls (t DM $year^{-1}$)	2.06 ± 0.03^b	1.22 ± 0.04^c	2.47 ± 0.04^a
Heifers/Subadult bulls (t DM $year^{-1}$)	5.91 ± 0.08^c	7.11 ± 0.09^b	12.65 ± 0.07^a
Calves (t DM $year^{-1}$)	1.52 ± 0.02^c	1.88 ± 0.02^b	4.08 ± 0.02^a
Total manure production (t DM $year^{-1}$)	18.22 ± 0.20^c	22.87 ± 0.17^b	47.03 ± 0.26^a
Manure applied			
Total manure applied per year (t DM $year^{-1}$)	12.70 ± 0.15^a	9.71 ± 0.25^b	2.47 ± 0.05^c
Manure applied per unit area of farmland (t DM ha^{-1} $year^{-1}$)	2 ± 0.02^b	2.89 ± 0.52^a	1.72 ± 0.01^c

a,b,c: Means with different letters on the same line differ significantly ($p < 0.05$).

Table 5
Reported crop residues use (%) in each cattle farming type.

Farming Types	Crop residues	Use as feed	Remaining on the field	Other uses[a]
Type 1	Groundnut	93	7	0
	Soybean	92	8	0
	Sorghum	68	12	20
	Maize	67	13	20
Type 2	Forage crop	0	100	0
	Soybean	92	8	0
	Sorghum	67	9	24
	Maize	65	12	23
Type 3	Millet	73	8	19
	Sorghum	68	5	27
	Maize	69	7	24

[a] Other: includes use as domestic energy, roofing and fencing materials.

3.3.2. Biomass production from crop residues

Crop yields varied ($p<0.05$) from one cattle farming type to another (Table 6). For the same crop encountered in the three cattle farming types, the best yields were recorded in farms type 1 followed by farms type 2.

The total amounts of crop residues produced varied significantly from one cattle farming type to another ($p<0.05$). Thus, the total crop residues produced in farms type 1 was the highest (2.97 ± 0.03 t DM ha^{-1}) while that produced in farms type 3 was the lowest (1.41 ± 0.04 t DM ha^{-1}). The amount of crop residues remaining on the field was higher in farms type 2 (794.24 ± 13.99 kg DM ha^{-1}) than in the other two types.

3.4. Carbon input from manure and crop residues

Table 7 presents C inputs from manure and crop residues. The amounts of C from total manure production per year and applied per unit area of farmland varied ($p<0.05$) from one cattle farming type to another. Among all cattle farming types, the highest amount of C from total manure production was recorded in farms type 3 (19.93 ± 0.10 t C $year^{-1}$). Likewise, the lowest amount of C from applied manure was always observed in the same type (727.47 ± 6.94 kg C ha^{-1} $year^{-1}$).

Carbon inputs from crop residue production and remaining on the field were different ($p < 0.05$) for the three types. The highest amount of C from the total crop residues production was observed in farms type 1 (1.34 ± 0.01 t C ha^{-1} $year^{-1}$), while the highest C from crop residues remaining on the field was recorded in type 2 (357.49 ± 6.29 t C ha^{-1} $year^{-1}$).

Table 6
Main product yield and crop residues production in each cattle farming type.

Parameters	Type 1	Type 2	Type 3
Maize yield (t DM ha^{-1})	2.22 ± 0.15^a	2.11 ± 0.05^b	1.38 ± 0.02^c
Sorghum yield (t DM ha^{-1})	0.92 ± 0.005^a	0.81 ± 0.01^b	0.68 ± 0.009^c
Millet yield (t DM ha^{-1})	–	–	1.21 ± 0.01
Soybean yield (t DM ha^{-1})	1.04 ± 0.006^a	0.97 ± 0.006^b	–
Groundnut yield (t DM ha^{-1})	0.71 ± 0.004	–	–
Forage crop yield (t DM ha^{-1})	–	3.81 ± 0.06	–
Total crop residues production (t DM ha^{-1})	2.97 ± 0.03^a	2.58 ± 0.07^b	1.41 ± 0.04^c
Total crop residues remaining on the field (kg DM ha^{-1})	324.37 ± 3.50^b	794.42 ± 13.99^a	127 ± 3.38^c

a,b,c: Means with different letters on the same line differ significantly ($p < 0.05$).

Table 7
Annual carbon input from each cattle farming type.

Parameters	Type 1	Type 2	Type 3
Carbon from manure			
C from total manure production per year (t C $year^{-1}$)	7.72 ± 0.08[c]	9.69 ± 0.07[b]	19.93 ± 0.10[a]
C from applied manure per unit area of farmland (kg C ha^{-1} $year^{-1}$)	849.11 ± 9.13[b]	1223.18 ± 16.71[a]	727.47 ± 6.94[c]
Carbon from crop residues			
C from total crop residues production (t C ha^{-1} $year^{-1}$)	1.34 ± 0.01[a]	1.16 ± 0.03[b]	0.63 ± 0.01[c]
C from crop residues remaining on the field (kg C ha^{-1} $year^{-1}$)	145.96 ± 1.58[b]	357.49 ± 6.29[a]	57.15 ± 1.52[c]

a,b,c: Means with different letters on the same line differ significantly ($p < 0.05$).

3.5. *Carbon sequestration in soil*

Annual soil C sequestration varied ($p<0.05$) from one cattle farming type to another (Fig. 2). Annual soil C sequestration was higher in farms type 2 (158.07 ± 1.79 kg C ha^{-1} $year^{-1}$) followed by farms type 1 (99.51 ± 0.95 kg C ha^{-1} $year^{-1}$), which had a higher value than farms type 3 (78.46 ± 0.70 kg C ha^{-1} $year^{-1}$). In all cattle farming types soil C_{seq} from manure contributed more to the total annual soil C sequestration, i.e. 85.32%, 77.37%, and 92.70% of the total respectively for types 1, 2, and 3.

4. Discussion

Cattle farms provide alternative employment opportunities in zones where other economic activities are not possible [47]. They contribute also to ecosystem services such as soil carbon sequestration [48]. This role is influenced by the practices implemented by cattle farmers [49]. In this study, we evaluated the effect of three farming practices in farmland soil carbon sequestration based on carbon inputs from manure and crop residues.

The results revealed that the annual manure production from cattle farms type 3 was the highest compared to the other two types of farms. This result could be explained by the difference in the cattle herd size between these cattle farming types. Other factors could also explain the difference in manure production between different farming systems. These factors are livestock breed, weight, feeding regimes, etc … [50]. The quantity of manure applied per unit area of farmland was lower in farms type 1 than in farms type 2. However, the crop yield per hectare was higher in farms type 1 than in farms type 2. This result is surprising because it was expected that crop yield would be higher in farms type 2 given that the quantity of manure applied per unit area of farmland in this farming type was higher. Indeed, several factors determine the obtaining of a better crop yield. This mainly concerns rainfall and the quantity of manure required per hectare. Farms type 1 was mainly located in the sub-humid zone where the rainfall is higher (1155 mm) than the dry zone (953 mm) where farms type 2 was mainly located. This could explain the results obtained. The application of manure to the soil provides nutrients to plants and this in turn increases agricultural yield. However, the overuse of manure applications poses serious environmental risks, when they are used without adequate treatments [51]. To prevent the application of manure from being a source of pollution, its quantity of application must be limited to 35 kg/ha [52].

In the different cattle farming types, crop residues have been valued in diverse ways by farmers. However, these residues were used the most in animal feed during the dry season. These results are similar to those obtained by other authors [53,54], who showed that crop residues are much more used in livestock feed in dry periods. While herbaceous fodder is abundant during the rainy season and can cover all the feed needs of the herds, in the dry season, herbaceous fodder becomes scarce [55]. Animal feed in the dry season is mainly provided by crop residues and woody fodder [56]. The use of crop residues by animals is a strategic and vital issue for farmers.

The total amount of crop residues produced varied from one type of farm to another, with high production in farms type 1. These variations would result from the combination of several factors, including the choice of crop plot, soil water, nutrient availability, soil fertility management, and cultivation techniques [53]. The amount of crop residues remains on the field varied with the type of farm. The highest amount was obtained in farms type 2. This result is the consequence of a large amount of *Panicum maximum* residue remaining on the field in this cattle farming type. In farms types 1 and 2 where cereals and legumes are grown, it was found that the amount of legume crop residues remaining on the field was lower than that of cereal crop residues remaining on the field. This result could be explained by the fact that legumes have a higher feed value than cereals and are therefore more palatable to animals [57]. Where available, livestock keepers appreciate legume residues, particularly for feeding animals [58].

In general, the values of soil C sequestered per hectare obtained in this study were higher than the values reported by Arca et al. [24] and Jia et al. [51]. Crop residues production and the equations used to estimate C input from crop residues and manure may explain the difference between our results and those of these authors. On the other hand, the values of soil C sequestration per hectare observed in this study were in line with the results obtained by other authors [6,9,59]. Farms type 2 had significantly higher soil C sequestration values per hectare of land use than farms types 1 and 3. This is because farms type 2 had higher C input from crop residues remains on the field and manure applied per unit area. Similar results were reported by Beniston et al. [60]. Considering the amount of soil C sequestered from crop residues only, it appears that the high value was always obtained in farms type 2. This result is proof that the forage crops (*Panicum maximum*) which distinguish this cattle farming type from the others bring enough benefits in terms of soil C sequestered. Thus, it can be considered a climate change mitigation strategy for the production system [61]. The amount of soil C sequestration from manure in farms type 3 was the lowest even though their total annual manure production was the highest. These results could be explained by the fact that farmers of this cattle farming type applied a low quantity of manure per hectare

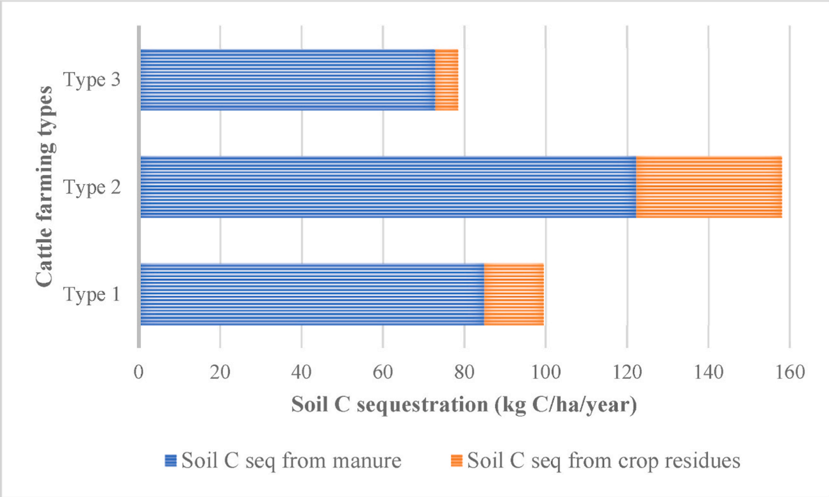

Fig. 2. Soil carbon sequestration in each cattle farming type.

compared to other types. Thus, the remaining proportion of manure produced that is not applied to farmland is either burned for fuel or disposed of altogether. Similar results were reported by Kimura et al. [33]. The Peterson et al. [23] approach used to estimate soil carbon sequestration in this study may have uncertainties. However, when comparing several methods, several authors revealed this approach based on real data on C inputs seems to give more precise and realistic results and thus allow mitigation strategies to be designed with greater precision [6,24].

5. Conclusion

This study estimated the amount of C sequestered in farmland soils of three cattle farming types in Benin through the C input from manure and crop residues. The simple quantification method used can be applied to any situation to gain insight into the amount of C sequestered in farmland soil. The results of this study revealed that the carbon inputs from manure and crop residues varied from one cattle farming type to another. Farms that integrated livestock with cereal-legume and forage crops had a higher soil carbon sequestration value followed by farms integrating livestock with cereal-legume crops and farms practicing pastoral mobility. The three cattle farming practices highlighted in this study each contributed in one way or another to sequestering carbon in the soil. These practices are well known by farmers and many cattle farmers are already benefiting from their implementation on their farms. For future research work aiming to assess the carbon footprint of these farms or any other livestock system in sub-Saharan Africa, it would be appropriate to take into account the amount of soil carbon sequestered in this assessment.

Data availability statement

Data will be made available on request.

Funding statement

This study was financed under the MOPGA program by the Ministries of Europe and Foreign Affairs (MEAE) and of Higher Education, Research, and Innovation (MESRI) of the Republic of France. This study was also financed by the French National Research Agency (ANR), as part of the “Investissements d’avenir” program, under the reference ANR-10-LABX-001-01 Labex Agro, and coordinated by Agropolis Fondation.

CRediT authorship contribution statement

Yaya Idrissou: Writing – review & editing, Writing – original draft, Project administration, Methodology, Formal analysis, Data curation, Conceptualization, Funding acquisition, Investigation. **Eric Vall:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Vincent Blanfort:** Writing – review & editing, Methodology. **Mélanie Blanchard:** Writing – review & editing. **Ibrahim Alkoiret Traoré:** Investigation, Conceptualization. **Philippe Lecomte:** Writing – review & editing.

Declaration of competing interest

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

Acknowledgments

This work is part of the visiting fellowship program for young researchers, Make Our Planet Great Again (MOPGA) implemented by the Ministries of Europe and Foreign Affairs (MEAE) and of Higher Education, Research, and Innovation (MESRI) in collaboration with Campus France. The authors thank the ANR (the French National Research Agency), as part of the "Investissements d'avenir" program, under the reference ANR-10-LABX-001-01 Labex Agro, and coordinated by Agropolis Fondation, the Government of the Republic of France as well as the MEAE, MESRI, and Campus France for their financial support.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e28748.

References

[1] IPCC, Climate Change 2014: Mitigation of Climate Change, Cambridge University Press., 2015.
[2] M.H. Assouma, D. Serça, F. Guérin, V. Blanfort, P. Lecomte, I. Touré, A. Ickowicz, R.J. Manlay, M. Bernoux, J. Vayssières, Livestock induces strong spatial heterogeneity of soil CO2, N2O and CH4 emissions within a semi-arid sylvo-pastoral landscape in West Africa, J. Arid Land 9 (2017) 210–221, https://doi.org/10.1007/s40333-017-0001-y.
[3] IPCC, AR6 Synthesis Report: Climate Change 2023, available at: https://www.ipcc.ch/report/sixth-assessment-report-cycle/, Cambridge University Press, Cambridge, United Kingdom and New York, YNY, USA, 2023.
[4] P.K. Thornton, P.J. Ericksen, M. Herrero, A.J. Challinor, Climate variability and vulnerability to climate change: a review, Global Change Biol. 20 (2014) 3313–3328, https://doi.org/10.1111/gcb.12581.
[5] P.J. Gerber, B. Henderson, H.P. Makkar, Mitigation of greenhouse gas emissions in livestock production: a review of technical options for non-CO2 emissions, Food and Agriculture Organization of the United Nations (FAO) (2013). https://www.cabdirect.org/cabdirect/abstract/20133374225. (Accessed 21 January 2024).
[6] I. Batalla, M.T. Knudsen, L. Mogensen, Ó. del Hierro, M. Pinto, J.E. Hermansen, Carbon footprint of milk from sheep farming systems in Northern Spain including soil carbon sequestration in grasslands, J. Clean. Prod. 104 (2015) 121–129, https://doi.org/10.1016/j.jclepro.2015.05.043.
[7] FAO, FAO Statistical Yearbook 2013: World Food and Agriculture, Éd, FAO, Rome, 2013, p. 289.
[8] M. Herrero, B. Henderson, P. Havlík, P.K. Thornton, R.T. Conant, P. Smith, S. Wirsenius, A.N. Hristov, P. Gerber, M. Gill, Greenhouse gas mitigation potentials in the livestock sector, Nat. Clim. Change 6 (2016) 452–461, https://doi.org/10.1038/nclimate2925.
[9] M.H. Assouma, P. Hiernaux, P. Lecomte, A. Ickowicz, M. Bernoux, J. Vayssières, Contrasted seasonal balances in a Sahelian pastoral ecosystem result in a neutral annual carbon balance, J. Arid Environ. 162 (2019) 62–73, https://doi.org/10.1016/j.jaridenv.2018.11.013.
[10] V. Blanfort, C. Stahl, Actes de la journée: le carbone en forêt et en prairies issues de déforestation en Guyane, processus, bilans et perspectives, 1er octobre 2013, Cayenne, Guyane française, in: Cirad, 2013. https://agritrop.cirad.fr/574455/1/document_574455.pdf. (Accessed 5 March 2024).
[11] D. Marone, V. Poirier, M. Coyea, A. Olivier, A.D. Munson, Carbon storage in agroforestry systems in the semi-arid zone of Niayes, Senegal, Agrofor. Syst. 91 (2017) 941–954, https://doi.org/10.1007/s10457-016-9969-0.
[12] A.-J.A. N'Goran, A.A. Diouf, S. Diatta, M.H. Assouma, A.J. Djagoun, G.G.C. Assogba, L. Cournac, L. Chapuis-Lardy, V. Blanfort, S. Taugourdeau, Variabilité des stocks de carbone du sol sous et hors houppier dans la zone sylvopastorale du Sénégal, Rev. D'élevage Médecine Vét. Pays Trop. 75 (2022) 67–75, https://doi.org/10.19182/remvt.36984.
[13] E. Vall, P. Salgado, C. Corniaux, M. Blanchard, C. Dutilly, V. Alary, Changements et innovations dans les systèmes d'élevage en Afrique, INRA Prod Anim 27 (2014) 161–174.
[14] Y. Idrissou, A.S. Assani, Y. Toukourou, H.S.S. Worogo, B.G.C. Assogba, M. Azalou, J.S. Adjassin, C.D.A. Alabi, J.A. Yabi, I.T. Alkoiret, Systèmes d'élevage pastoraux et changement climatique en Afrique de l'Ouest: Etat des lieux et perspectives, Livest. Res, Rural Dev. 31 (2019) 1–20.
[15] Y. Idrissou, D. Korir, A.A. Seidou, H.S.S. Worogo, M.N. Baco, I.A. Traoré, Adapting cattle farming to climate change in the dry and sub-humid tropical zones in Benin: how adaptation strategies affect productivity, Rev. D'élevage Médecine Vét. Pays Trop. 76 (2023) 1–10, https://doi.org/10.19182/remvt.37118.
[16] W. Snaibi, A. Mezrhab, Livestock breeders' adaptation to climate variability and change in Morocco's arid rangelands, in: W. Leal Filho, N. Oguge, D. Ayal, L. Adeleke, I. Da Silva (Eds.), Afr. Handb. Clim. Change Adapt., Springer International Publishing, Cham, 2021, pp. 1–20, https://doi.org/10.1007/978-3-030-42091-8_18-1.
[17] Y. Idrissou, A.S. Assani, M.N. Baco, A.J. Yabi, I.A. Traoré, Adaptation strategies of cattle farmers in the dry and sub-humid tropical zones of Benin in the context of climate change, Heliyon 6 (2020) e04373, https://doi.org/10.1016/j.heliyon.2020.e04373.
[18] I.T. Alkoiret, D.Y.G. Awohouedji, A.B. Gbangboche, R.H. Bosma, Productivité des systèmes d'élevage bovin de la commune de Gogounou au nord-est du Bénin, Ann. Sci. Agron. 14 (2010), https://doi.org/10.4314/asab.v14i2.67360.
[19] R.C. Toko, A. Adégbidi, P. Lebailly, Démographie et performances zootechniques des élevages bovins traditionnels au Nord Bénin, Rev. D'élevage Médecine Vét. Pays Trop. 69 (2016) 33–39, https://doi.org/10.19182/remvt.31169.
[20] IPCC, IPCC guidelines for national greenhouse Gas inventories, in: Intergovernmental Panel of Climate Change (IPCC), 2006. National Greenhouse Gas Inventories Programme. Online at. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.
[21] L.M. Vleeshouwers, A. Verhagen, Carbon emission and sequestration by agricultural land use: a model study for Europe, Global Change Biol. 8 (2002) 519–530, https://doi.org/10.1046/j.1365-2486.2002.00485.x.
[22] J.-F. Soussana, T. Tallec, V. Blanfort, Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands, Animal 4 (2010) 334–350, https://doi.org/10.1017/S1751731109990784.
[23] B.M. Petersen, M.T. Knudsen, J.E. Hermansen, N. Halberg, An approach to include soil carbon changes in life cycle assessments, J. Clean. Prod. 52 (2013) 217–224, https://doi.org/10.1016/j.jclepro.2013.03.007.
[24] P. Arca, E. Vagnoni, P. Duce, A. Franca, How does soil carbon sequestration affect greenhouse gas emissions from a sheep farming system? Results of a life cycle assessment case study, Ital. J. Agron. 16 (2021), https://doi.org/10.4081/ija.2021.1789.
[25] C.P. Gnanglè, R.G. Kakaï, A.E. Assogbadjo, S. Vodounnon, J.A. Yabi, N. Sokpon, Tendances climatiques passées, modélisation, perceptions et adaptations locales au Bénin, Climatologie 8 (2011) 27–40, https://doi.org/10.4267/climatologie.259.
[26] MEHU, Deuxième Communication Nationale de la République du Bénin sur les Changements Climatiques, Cotonou Ministère L'Environnement L'Habitat L'Urbanisme, 2011.
[27] T.I. Alkoiret, M. Radji, S. Babatoundé, Typologie des élevages bovins installés dans la commune de Ouaké au nord-ouest du Bénin, Livest. Res, Rural Dev. 23 (2011) 1–12.

[28] A.E. Assogbadjo, R.G. Kakaï, F.G. Vodouhê, C. Djagoun, J.T.C. Codjia, B. Sinsin, Biodiversity and socioeconomic factors supporting farmers' choice of wild edible trees in the agroforestry systems of Benin (West Africa), for, Policy Econ. 14 (2012) 41–49, https://doi.org/10.1016/j.forpol.2011.07.013.
[29] Y. Idrissou, Y.M.S. Seidou, A.A. Seidou, H.S. Worogo, B.G.C. Assogba, I.A. Traoré, M. Houinato, Influence of grazing and climatic gradient on the floristic diversity and productivity of rangelands in Benin, Rev. D'élevage Médecine Vét. Pays Trop. 73 (2020) 1–7, https://doi.org/10.19182/remvt.31894.
[30] A. Natta, Ecological Assessment of Riparian Forests in Benin: Phytodiversity, Phytosociology and Spatial Distribution of Tree Species, PhD Thesis, Wageningen University, Wageningen, Netherlands, 2003, p. 215.
[31] A.C. Adomou, B. Sinsin, V. der Maesen, L.J. Gerardus, Phytosociological and chorological approaches to phytogeography: a meso-scale study in Benin, Syst. Geogr. Plants 76 (2006) 155–178.
[32] P. Neuenschwander, B. Sinsin, G.E. Goergen, Protection de la nature en Afrique de l'Ouest: une liste rouge pour le Bénin, in: International Institute of Tropical Agriculture, 2011. https://biblio1.iita.org/bitstream/handle/20.500.12478/1965/U11BkNeuenschwanderNothomDev.pdf-37b29d538e696f8f6cb24b648a62164d.pdf?sequence=1. (Accessed 16 February 2024).
[33] S.D. Kimura, S.-I. Mishima, K. Yagi, Carbon resources of residue and manure in Japanese farmland soils, Nutrient Cycl. Agroecosyst. 89 (2011) 291–302, https://doi.org/10.1007/s10705-010-9394-0.
[34] H.D. Braber, G. Van De Ven, E. Ronner, W. Marinus, A. Languillaume, D. Ochola, G. Taulya, K.E. Giller, K. Descheemaeker, Manure matters: prospects for regional banana-livestock integration for sustainable intensification in South-West Uganda, Int. J. Agric. Sustain. 20 (2022) 821–843, https://doi.org/10.1080/14735903.2021.1988478.
[35] Y. Xin, D. Wang, X.Q. Li, Q. Yuan, H. Cao, Influence of moisture content on cattle manure char properties and its potential for hydrogen rich gas production, J. Anal. Appl. Pyrolysis 130 (2018) 224–232, https://doi.org/10.1016/j.jaap.2018.01.005.
[36] S.S. Toléba, A.K.I. Youssao, M. Dahouda, U.M.A. Missainhoun, G.A. Mensah, Identification et valeurs nutritionnelles des aliments utilisés en élevage d'aulacodes (Thryonomys swinderianus) dans les villes de Cotonou et Porto-Novo au Bénin, Bull. Rech. Agron. Bénin 64 (2009) 1–10.
[37] K. Adéoti, S.H. Kouhoundé, P.A. Noumavo, F. Baba-Moussa, F. Toukourou, Nutritional value and physicochemical composition of pearl millet (Pennisetum glaucum) produced in Benin, J. Microbiol. Biotechnol. Food Sci. 7 (2017) 92–96, https://doi.org/10.15414/jmbfs.2017.7.1.92-96.
[38] G.S.T. Atchade, E.F. Segbotangni, S.E.P. Mensah, M.F. Houndonougbo, S.E. Attakpa, C. Cryssostome, Les grains de céréale dans l'alimentation des poulets au Bénin: digestibilité métabolique et paramčtres biochimiques sériques induits', Afr. Sci. 15 (2019) 25–38.
[39] Y. Idrissou, H.S.S. Worogo, A.S. Assani, J.A. Ayena, B.G.C. Assogba, I.A. Traoré, Cottonseed cake replacement by soybean pulp in the diet of West African Dwarf lambs in Benin: zootechnical and economic performances, Rev. D'élevage Médecine Vét. Pays Trop. 73 (2020) 107–111, https://doi.org/10.19182/remvt.31875.
[40] M.A. Bolinder, H.H. Janzen, E.G. Gregorich, D.A. Angers, A.J. VandenBygaart, An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada, Agric. Ecosyst. Environ. 118 (2007) 29–42, https://doi.org/10.1016/j.agee.2006.05.013.
[41] R. Serraj, C.T. Hash, S.M.H. Rizvi, A. Sharma, R.S. Yadav, F.R. Bidinger, Recent advances in marker-assisted selection for drought tolerance in pearl millet, Plant Prod, Science 8 (2005) 334–337, https://doi.org/10.1626/pps.8.334.
[42] S.O. Oikeh, V.O. Chude, G.J. Kling, W.J. Horst, Comparative productivity of nitrogen-use efficient and nitrogen-inefficient maize cultivars and traditional grain sorghum in the moist Savanna of West Africa, Afr. J. Agric. Res. 2 (2007) 112–118.
[43] G. Guimbirke, La nodulation de l'arachide indicateur de l'acidité des sols au nord Cameroun, PhD Thesis, IRAD, https://agritrop.cirad.fr/570260/, 2012. (Accessed 21 January 2024).
[44] P.G. Tovihoudji, P.I. Akponikpè, E.K. Agbossou, P. Bertin, C.L. Bielders, Fertilizer microdosing enhances maize yields but may exacerbate nutrient mining in maize cropping systems in northern Benin, Field Crops Res. 213 (2017) 130–142, https://doi.org/10.1016/j.fcr.2017.08.003.
[45] O.C. Faki, D.D. Gustave, C.A. Emile, T.O. Brice, K.A. Bérékia, D. Mireille, E.A. Léonard, L.A. Guillaume, A. Saïdou, Fertilizer recommendations for optimal soybean production in North and Center Benin, J. Soil Sci. Environ. Manag. 12 (2021) 29–43, https://doi.org/10.5897/JSSEM2021.0860.
[46] R Core Team Development, R, A Language and Environment for Statistical Computing, URL Http://Www. R-Project. Org, R Foundation for Statistical Computing, Vienna, Austria, 2012, 2018.
[47] Y. Mena, J. Ruiz-Mirazo, F.A. Ruiz, J.M. Castel, Characterization and typification of small ruminant farms providing fuelbreak grazing services for wildfire prevention in Andalusia (Spain), Sci. Total Environ. 544 (2016) 211–219, https://doi.org/10.1016/j.scitotenv.2015.11.088.
[48] R.P. Udawatta, S. Jose, Agroforestry strategies to sequester carbon in temperate North America, Agrofor. Syst. 86 (2012) 225–242, https://doi.org/10.1007/s10457-012-9561-1.
[49] M. Escribano, A. Elghannam, F.J. Mesias, Dairy sheep farms in semi-arid rangelands: a carbon footprint dilemma between intensification and land-based grazing, Land Use Pol. 95 (2020) 104600, https://doi.org/10.1016/j.landusepol.2020.104600.
[50] J. Zake, J.S. Tenywa, F. Kabi, Improvement of manure management for crop production in Central Uganda, J. Sustain. Agric. 34 (2010) 595–617, https://doi.org/10.1080/10440046.2010.493368.
[51] W. Jia, W. Qin, Q. Zhang, X. Wang, Y. Ma, Q. Chen, Evaluation of crop residues and manure production and their geographical distribution in China, J. Clean. Prod. 188 (2018) 954–965, https://doi.org/10.1016/j.jclepro.2018.03.300.
[52] J.J. Schröder, J.J. Neeteson, Nutrient management regulations in The Netherlands, Geoderma 144 (2008) 418–425, https://doi.org/10.1016/j.geoderma.2007.12.012.
[53] M.-P. Hiel, S. Barbieux, J. Pierreux, C. Olivier, G. Lobet, C. Roisin, S. Garré, G. Colinet, B. Bodson, B. Dumont, Impact of crop residue management on crop production and soil chemistry after seven years of crop rotation in temperate climate, loamy soils, PeerJ 6 (2018) e4836, https://doi.org/10.7717/peerj.4836.
[54] G.L. Djohy, B.S. Bouko, G. Djohy, P.J. Dossou, J.A. Yabi, Contribution des résidus de culture à la réduction du déficit alimentaire des troupeaux de ruminants dans l'Ouémé Supérieur au Bénin, Cah, Agric. For. 32 (2023) 13, https://doi.org/10.1051/cagri/2023007.
[55] S. Douma, S. Diatta, C.Y. Kabore-Zoungrana, M. Banoin, L.E. Akpo, Caractérisation des terres de parcours sahéliennes: typologie du peuplement ligneux de la Station sahélienne Expérimentale de Toukounous au Niger, J. Sci. 7 (2007) 1–16.
[56] G.L. Djohy, B.S. Bouko, Vulnérabilité et dynamiques adaptatives des agropasteurs aux mutations climatiques dans la commune de Tchaourou au Bénin, Rev. D'élevage Médecine Vét. Pays Trop. 74 (2021) 27–35, https://doi.org/10.19182/remvt.36319.
[57] D. Valbuena, O. Erenstein, S.H.-K. Tui, T. Abdoulaye, L. Claessens, A.J. Duncan, B. Gérard, M.C. Rufino, N. Teufel, A. van Rooyen, Conservation agriculture in mixed crop–livestock systems: scoping crop residue trade-offs in Sub-Saharan Africa and South Asia, Field Crops Res. 132 (2012) 175–184, https://doi.org/10.1016/j.fcr.2012.02.022.
[58] S. Homann, A.F. Van Rooyen, T. Moyo, Z. Nengomasha, Goat production and marketing: baseline information for semi-arid Zimbabwe, in: International Crops Research Institute for the Semi-arid Tropics, 2007, p. 84. http://oar.icrisat.org/id/eprint/397. (Accessed 21 January 2024).
[59] F. Zhang, S. Wang, M. Zhao, F. Qin, X. Liu, Regional simulation of soil organic carbon dynamics for dry farmland in Northeast China using the CENTURY model, PLoS One 16 (2021) e0245040, https://doi.org/10.1371/journal.pone.0245040.
[60] J.W. Beniston, S.T. DuPont, J.D. Glover, R. Lal, J.A.J. Dungait, Soil organic carbon dynamics 75 years after land-use change in perennial grassland and annual wheat agricultural systems, Biogeochemistry 120 (2014) 37–49, https://doi.org/10.1007/s10533-014-9980-3.
[61] G. Gislon, F. Ferrero, L. Bava, G. Borreani, A. Dal Prà, M.T. Pacchioli, A. Sandrucci, M. Zucali, E. Tabacco, Forage systems and sustainability of milk production: feed efficiency, environmental impacts and soil carbon stocks, J. Clean. Prod. 260 (2020) 121012, https://doi.org/10.1016/j.jclepro.2020.121012.