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Understanding farm-level diversity to guide soil fertility management in West African cotton systems: Evidence from Benin

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A B S T R A C T

Although cotton cultivation grants farmers access to annual inputs of mineral fertilisers, there is a generalised tendency of soil fertility decline in Benin's cotton-growing area. This study aimed to understand the link between farm socioeconomic diversity, soil management practices, and soil fertility status in cotton-based farming system of Benin. Socio-demographic and farm management data were collected from 242 farms on three sites in southern-central and northern Benin. Principal component analysis and a hierarchical clustering were used to construct a farm typology. Soil management practices were analysed in the light of this typology. Composite soil samples 20 cm deep were then taken from 40 plots representing the farm/soil types identified, to assess variability in soil fertility as influenced by farm types and management practices. Four farm types emerged, differing in resource endowments and soil management practices. Practices such as manure application (92 %) and rotational herd corralling (42 %) were adopted more often by livestock owners. Farms without livestock implemented practices such as crop rotation (90 %) and intercropping (41 %). Soil fertility status was low to very low in all farms sampled across the three sites (extractable phosphorus <10 mg P/kg soil, soil organic matter < 20 g kg^{-1} soil). Although a link between farms' soil management practices and soil fertility status was expected, no statistical differences were detected across farm types ($p > 0.05$). Cotton yields, as declared by farmers, were also not statistically associated with soil fertility levels. The generalized poor fertility status of soils that receive annual fertilizer inputs suggests that this practice is not enough to maintain long-term soil productivity in the climatic and soil conditions of Benin cotton zones studied here. This was also the case in fields that received combinations of mineral fertiliser and animal manure, which is probably not used in sufficient quantity and quality. Low organic matter inputs, crop residue removal and conventional tillage, as practiced by the majority of farmers in our study sites (100 %), may contribute to explain the low levels of SOM and organically-held nutrients in the soil. Alternative measures to maintain soil fertility should be further investigated locally for their capacity to restore and maintain soil fertility in the long term and to improve crop yields, considering the socioeconomic diversity of farms and their environment.

1. Introduction

Cotton is the major crop grown by smallholder farmers in Benin, representing 40 % of the national domestic product and 80 % of exports (Ollabodé et al., 2024). As in most farming systems of sub-Saharan Africa (SSA), agricultural production in Benin faces major challenges linked to climatic variability, declining soil fertility, low levels of mechanization and farmer organization in rural areas (Omotoso et al., 2023; Suri and Udry, 2022; Tully et al., 2015). Soil fertility decline has been reported as one of the major challenges faced by cotton farmers due

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to structural problems such as land tenure or livestock population densities (Asaaga et al., 2020; Yemadje et al., 2014), but also to unsustainable agricultural practices (Dossouhoui et al., 2023; Amonmide et al., 2019). Despite the promotion of soil fertility management strategies such as integrated soil fertility management (ISFM) (Bayu, 2020; Wezel et al., 2014) or conservation agriculture (CA) (Yemadje et al., 2022, 2025) soil fertility keeps declining and remains a major concern in the region (Hounkpatin et al., 2022).

In Benin, cotton production is rainfed and dominated by smallholders practicing contract farming, who receive inputs of fertilizers, seeds and agrochemicals from cotton firms, which are paid for with part of the harvest at the end of the season (Olounlade et al., 2020). Often, part of the fertilizer farmers get through these schemes is used to fertilize food crops, chiefly maize, which is grown in rotation with cotton (Tovihoudji et al., 2023). However, farmers are diverse across the vast cotton growing regions of Benin, differing in their levels of resource endowment, experience, and farming strategies, and any strategy to revert soil fertility decline must embrace such diversity. Recognizing the diversity of farm households within and between regions, is the first step in designing policies and technical recommendations, targeting innovations, and understanding how specific objectives and resource endowments affect resource allocation leading to soil heterogeneity and fertility status (Tittonell et al., 2010; Alvarez et al., 2018; Huber et al., 2024).

Several studies have addressed farm diversity based on factors such as biophysical and socio-economic contexts, land tenure systems, farmers' agronomic and livelihood diversification strategies, land use, and labour availability (Musumba et al., 2022; Abera et al., 2021; Asaaga et al., 2020; Hauswirth et al., 2015; Tittonell et al., 2005). Taking this diversity into account is essential to avoid designing sustainable intensification practices that do not fit the needs and contexts of individual households (Oyetunde-Usman et al., 2021; Descheemaeker et al., 2019; Valbuena et al., 2015). In several sub-Saharan countries, as well as in Benin, resource-endowed farmers have access to large quantities of manure and mineral fertilizers (Diarisso et al., 2015), which help to increase soil fertility and crop productivity on their farms. However, resource-poor farmers must rely on off-farm income opportunities such as selling their labour to other farmers or migrate to urban areas (Chikowo et al., 2014). Despite the close link between farm endowments, productivity and resources, the diversity sometimes observed within farm types in West Africa can make it challenging to link a given household type to a given management type or fertility level (Berre et al., 2022). Moreover, the well-known patterns described in other rural regions of SSA in terms of farm diversity and soil fertility status and heterogeneity (e.g., Zingore et al., 2007; Tittonell et al., 2005; Samaké et al., 2005; Carter and Murwira, 1995) may not necessarily hold in cotton growing regions of Benin, where virtually all farmers access annual inputs of mineral fertilizer through contract farming.

In the quest for entry points to redress soil fertility decline, our study aims to characterize the diversity of soil management practices implemented by different types of farmers and their impact on soil fertility status in cotton-based cropping systems of Benin. Recognizing that soil variability and the diversity of agricultural practices require a multiscale approach, our study integrates a statistical typology of farms with targeted soil sampling in three distinct agro-ecological zones in Benin's cotton-growing regions. This integrated framework captures the inherent heterogeneity in soil types, current heterogeneity in soil fertility status, and the diversity of management practices. We hypothesize that although nearly all farmers use mineral fertilizers accessible via cotton companies, the adoption of additional soil management practices is influenced by farm-specific attributes such as resource endowment, production orientation, and household composition, resulting in measurable differences in soil fertility outcomes. Understanding these choices and their effects will help identify targeted strategies for restoring soil fertility, thereby contributing to sustainable improvements in agricultural production and farmers' livelihoods.

2. Materials and methods

2.1. Study area

The study was conducted in Benin, located in tropical West Africa, between latitudes 6°30' and 12°30' North and longitudes 1° and 3°40' East. Three cotton-growing areas (Kandi, Pehunco, Savalou) located in three different agro-ecological zones were selected (Table 1). One site was selected at each municipality, Angaradebou (11°19' 44°N and 3°02' 26° E), Pehunco (10°9' 59° N and 1°57'N and 14°E) and Tchetti (7°49' 49°N and 1°39'43°E) respectively in Kandi, Pehunco and Savalou (Fig. 1).

These sites were selected because of their contrasting climatic, agricultural and livestock density conditions. Most agricultural production in Kandi and Pehunco sites takes place in a single rainy season, as they have a dry tropical climate with alternating wet (May to October) and dry seasons (November to April). The Savalou site has a bimodal climate with high humidity. Alternating dry seasons (November to March and mid-July to mid-September) and rainy seasons (April to mid-July and mid-September to October) (Diogo et al., 2021; Azontondé et al., 2016; Gnanglè et al., 2011)

2.2. Surveys and data collection

2.2.1. Farm characterisation and management practices

An individual semi-structured questionnaire was designed and administered to the farm head. Two hundred and forty-two (242) farmers were interviewed between August and October 2022, i.e., 80 farmers in Kandi, 78 in Pehunco, and 84 in Savalou. The farms were selected using a simple random snowball sampling procedure. All participants agreed to take part in the survey. The collected data covered the demographic and socio-economic characteristics of the farms, farm management (cropping and livestock systems, different land and livestock management practices), household resource endowment, and production management (quantity produced, share consumed and sold). In the context of the study, each household managed a farm, so the words "household" and "farm" were used interchangeably (Assogba et al., 2022). The financial flows at the farm level were calculated based on information provided by farmers (Supplementary Materials File 2). The data collected includes the total production per crop (cotton, maize, cowpea, soybean, groundnut, sorghum), the proportion sold, and the selling price per kilogram. For livestock, the information covers number of cattle, sheep, poultry, and eggs sold during the year, as well as their unit selling price. The income per crop was determined by multiplying the quantity sold by the average selling price per kilogram or per unit. Regarding non-agricultural income, farmers estimated their annual gross income from these activities. The total income was then calculated by summing the income from crops, livestock, and non-agricultural activities. Finally, the share of non-agricultural income was expressed as a percentage of the total income for each farm.

2.2.2. Case study fields

To assess the status of soil fertility on farms, three representative farms were sampled per site and per farm type derived from the statistical typology. On farms with several fields located at least one km away from each other, two fields were sampled within these farms according to the level of soil fertility declared by the farmers (fertile and non-fertile). This gave us a composite sample for farms that had all their fields together and two soils composite samples for those that had several fields apart. Forty (40) case study fields were sampled that represented the diversity of sites and farm types identified. 90 % of the fields sampled were under cotton-based cropping systems, respectively, 100 % in Kandi, 84 % in Pehunco and 83 % in Savalou systems (Fig S4). Cotton and maize were managed following the practices recommended by the extension services in the study area (Yemadje et al., 2025; Zohoungbogbo et al., 2018; Hougni et al., 2016). Soil chemical

Table 1
The main characteristics, socio-economic indicators and production activities of the three sites.

Variables	Units	Sites		
Agro-ecological zone		**II (Northern Benin cotton zone)**	**III (South Borgou food-crops zone)**	**V (Central Benin cotton zone)**
Biophysical characteristics		**Kandi**	**Pehunco**	**Savalou**
Geographic coordinates	degree	11° 07′ 43″ N, 2° 56′ 13″ East	10° 13′ 42″ N, 2° 00′ 07″ East	7° 55′ 50″ N, 1° 58′ 31″ E
Altitude	m	300	389	181
Annual mean temperature	°C	28	26	24
Annual rainfall		1000 ± 220 mm	1123 ± 185 mm	1410 ± 370 mm
Rainy season		May to October	May to October	April to mid-July and mid-September to October
Topography	%	Gently rolling peneplain (slope between 1 and 4).	Gourma peneplain to the west and Atacora chain to the east	Crystalline peneplain with isolated domes (3–10 slope)
Soil type (Dominant) (https://soilgrids.org/ accessed on 11/9/2024)		Acrisols	Acrisols	Acrisols
Socio-economic indicators				
Population density (INStaD, 2018)	Hab/ km²	52	41	54
Population size (INStaD, 2018)	Hab	179,290	78,217	144,549
Ethnic group		Bariba, Mokole, Dendi, M'bo	Bariba	Nago, Mahi
Production activities				
Food crops		Maize, sorghum, millet, cowpea, groundnut	Maize, sorghum, millet, cowpea, groundnut	Maize, cowpea, groundnut, yam
Cash crops		Cotton, soybean, cashew, shea	Cotton, soybean, cashew, chea	Cotton, soybean, cashew
Breeding system		Dominated by cattle, sheep, guinea fowl and chicken.	Dominated by cattle, sheep, guinea fowl and chicken.	Dominated by goats and chicken

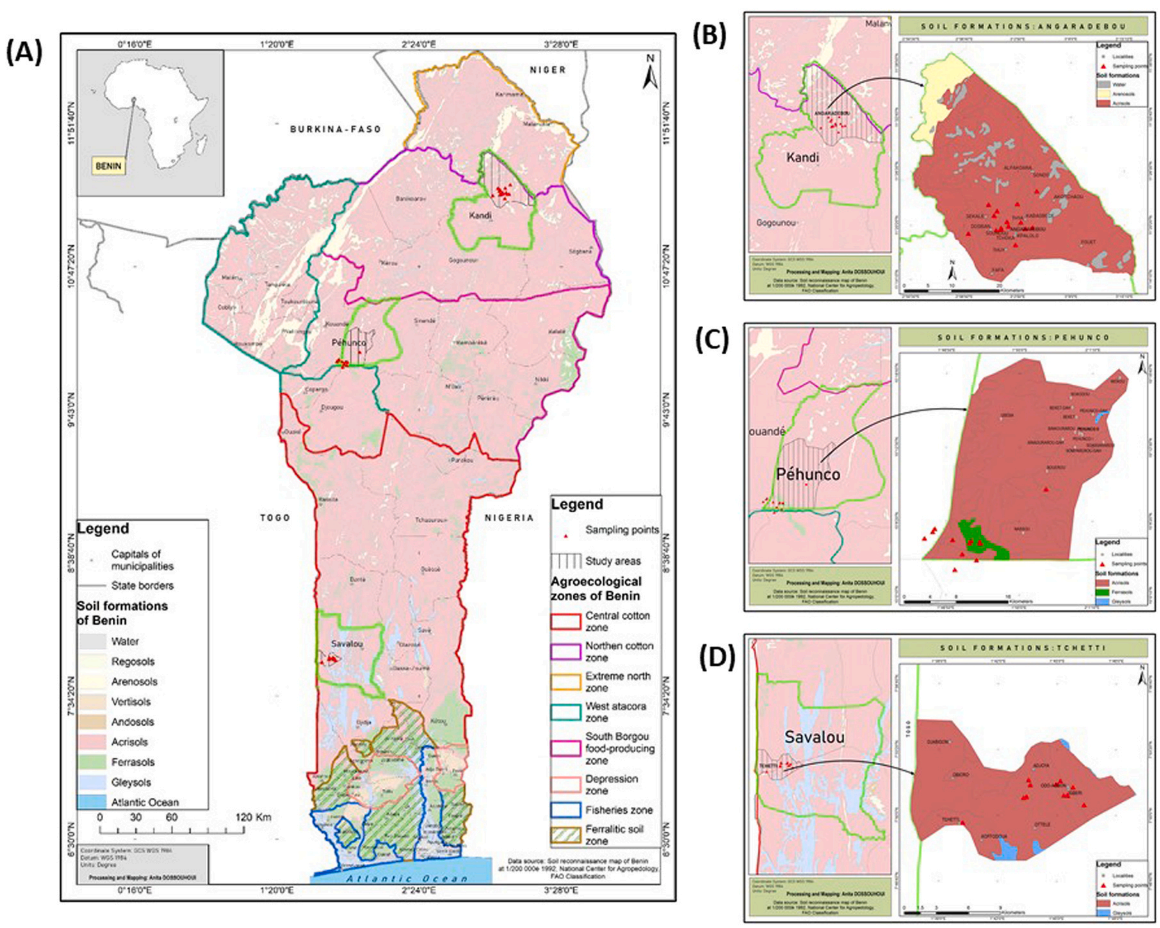

Fig. 1. Map of Benin showing the different agro ecological zones, soils type and study sites.

properties were measured in the composite samples from the case study fields, i.e., macronutrient content (total nitrogen, available phosphorus and potassium), organic carbon, soil pH and organic matter content, and particle size distribution (clay, fine and coarse silt, fine and coarse sand).

2.3. Data analysis

2.3.1. Farm typology

To construct farm typology, some studies have deployed an expert-based method, which consists of aggregating farms in clusters defined by local experts, key informants, or farmers (Assogba et al., 2022; Alvarez et al., 2014). However, the statistical method using multivariate analysis is the most commonly applied approach due to its reliability (Berre et al., 2022; Hammond et al., 2020; Tittonell et al., 2010; Dossa et al., 2011; Alary et al., 2002). First, a principal component analysis (PCA) was implemented to identify the main discriminating variables (Table 2) that summarize the diversity of the sample into a few principal components (dimension reduction process). Then, a hierarchical clustering on these principal components permitted distinct groups of farms (Berre et al., 2022; Alvarez et al., 2018; Tittonell et al., 2010). Analyses were performed with R software using the FactoMiner and FactoExtra package. Other variables, such as the percentage of land allocated to cotton, cereals, legumes, and cereal sold, were used as exogenous variables to describe the different farm types *a posteriori*. A one-factor analysis of variance was performed on these variables to highlight the differences between types of farm.

2.3.2. Management practices

Various farm management practices were mentioned by the farmers. Cultivation practices related to soil management were selected (Table 3). The proportion of farmers using these practices was then calculated for each farm type found in the typology and the sites.

2.3.3. Soil fertility assessment

The granulometry of the samples was obtained by determining the five particle size classes using the pipette method after the destruction of the oxygenated organic matter with hydrogen Peroxide (H_2O_2, 30 %) (Orzechowski et al., 2014; Miller and Miller, 1987). The pH was measured using a combined glass electrode soaked in a soil suspension in a Volume/Volume ratio of 5 (1/5 Soil/Water) in water, and the reading was taken by a pH meter (Bargrizan et al., 2017; Schofield and Taylor, 1955). Total organic carbon (OC) and total nitrogen were obtained after dry combustion and quantified by gas chromatography after appropriate calibration (Nelson and Sommers, 1996). The organic matter content was obtained from the formula OM%= OC%* 1.724. Available phosphorus was extracted using the Olsen method (Olsen, 1954), which involves extraction with a sodium bicarbonate solution at pH 8.5 in a m/V ratio of 1/20. Exchangeable potassium was obtained by the ammonium acetate method at pH 7.0 (Mehlich, 1953) and quantified by ICP spectrometry (Rowland and Haygarth, 1997). To guide the interpretation of soil physicochemical characteristics the criteria for assessing soil fertility classes in Benin proposed by Igue et al. (2013) was followed (Table 4). Although not universally applicable, these thresholds were derived from empirical studies carried out in West Africa and considered regional references (Dabin, 1970a, 1970b; Pieri and Moreau, 1987). They do not indicate the threshold at which there may or may not be a response to fertilizer application. Rather, they indicate the thresholds below which the value of the soil chemical fertility may represent a limit (moderate, severe) for agricultural production in the region. These thresholds have been recently used in other studies in the region (e.g., Koné et al., 2022; Nguemezi et al., 2020). Differences in soil chemical properties were analyzed using simple linear models, to assess the presence or absence of statistical differences in soil fertility level between sites and farm types. Soil chemical parameters were compared between zones and between farm types in relation to cotton yields obtained from farmers' declarations. We have confidence in the yield data because the producers obtain their production after weighing it using scales certified at the start of each season by Benin's National Standards and Meteorology Agency at the time of sale.

Table 2
Description of variables used for the principal component analysis.

Variable	Description
Experience	Head of household's farming experience (years)
Land_cult	Total area cultivated (ha)
Land_cotton	Cotton area (ha)
Adult Equivalent	Estimated household size in equivalent adults, calculated according to the Oxford scale (OECD, 1982; Queisser et al., 2022).(unit)
Off_farm	Proportion of household income from non-farming activities (%)
Cattle	Herd size (TLU)

NB. One cattle= 0.8 TLU (Diogo et al., 2010; FAO, 1984).

Table 3
Soil management practices.

Practices	Description
Crop rotation	Succession of crops over the years on the same plot
Intercropping	Association of several plant species on the same plot
Minimum tillage	Soil preparation technic localized on the sowing lines
Rotational herd corralling	Night-time stabling of livestock on a plot to be fertilized, which by day has already grazed other land
Manure application	Application of manure (dejection+urine) sometimes mixing biomass on a plot
Fodder legumes	Production of plants or mixtures of plants (grasses or legumes) with the main aim of feeding livestock

Table 4
Local reference values as evaluation criteria for soil fertility classes.

Soil properties	Cluster 1 (no limitation)	Cluster 2 (moderate limitation)	Cluster 3 (severe limitation)	Cluster 4 (very severe)
Soil Organic Carbone (g kg^{-1})	> 11.6	5.8–11.6	2.9–5.8	< 2.9
N (g kg^{-1})	> 0.8	0.4–0.8	0.3–0.45	< 0.3
Pass Olsen (mg/kg)	> 15	11–14	6–10	< 5
K^+ ech (meq/ 100 g)	> 0.4	0.2–0.4	0.1–0.2	< 0.1
pH (H_20)	5.5–6.5	5.5–6.5	5.3–5.2	< 5.2

Source: (Hounkpatin et al#, 2022; Amonmide et al#, 2019; Hazelton and Murphy, 2016; Mallarino et al#, 2013; Igue et al#, 2013; Dabin, 1970a)

3. Results

3.1. Farm diversity

The principal component analysis followed and hierarchical clustering performed revealed four types of farms (Fig S1). The first three components of the PCA summarized 69.3 % of the variance (Fig S1). The first component was associated with the area under cotton and the total area cultivated, which contributed respectively 42 % and 41 % to its variance (Fig S1). The second component was associated with livestock density per household, which accounts for 46 % of its variance. The proportion of household income originating from off-farm activities contributed 67 % of the variance of component 3.

The four resulting farm types across the three sites (Table 5, Fig S1) were characterised as follows:

- Type 1 (n = 46) = ***Diversified Income farms (DIF)***: this type is characterized by small farms with 34 % of their income originating from off-farm activities. Off-farm income originated either from the practice of local transport known locally as "*Zemidjan*", which consists of transporting people or goods on motorcycles, or from collecting and trading grain. Some famers operate as intermediaries for traders, their role being to collect the grain produced in their locality and deliver it to the traders from whom they obtain financial advantages. They cultivate an average of 5 ha of land, 43 % of which is allocated to cereals and 24 % to cotton (Fig. 2A). 71.7 % of farms belonging to this farm type include legume crop in their cropping system rotation (Fig S4). Most of the farms in this group have no livestock, only a few have cattle (1.8 TLU). This group has an average

Table 5
Characteristics of farm types (Mean ± standard deviation) across sites, and site by site.

	Farm Type	n	Variable used for typology						Other variable of interest				
			Years of farming experience	**Total cultivated area (ha)**	**Cotton Area (ha)**	**Adult Equivalent (unit)**	**Off-farm (%)**	**Cattle (TLU)**	**Land allocated to cotton (%)**	**Land allocated to cereal (%)**	**Land allocated to legume (%)**	**Cereal Sold (%)**	**Active household size**
ALL DATA	**DIF**	**46**	19.3 ± 1.6	5.0 ± 0.8**b**	1.2 ± 0.5**b**	8.5 ± 0.8	34.5 ± 0.0**a**	1.8 ± 1.3**b**	24 ± 3.3**b**	43 ± 3	33 ± 3.8**a**	56 ± 4.3**a**	8.6 ± 0.6**a**
	APF	**25**	29.4 ± 2.1	4.8 ± 1.1**b**	1.2 ± 0.6**b**	9.7 ± 1	5.7 ± 0.0**b**	40.7 ± 1.7**a**	18 ± 4.5**b**	35 ± 4	47 ± 5.1**a**	33 ± 6**b**	7.9 ± 0.8**a**
	SCF	**155**	17.6 ± 0.8	6.5 ± 0.5**b**	2 ± 0.2**b**	9.3 ± 0.4	1.3 ± 0**b**	3 ± 0.7**b**	31 ± 1.8**b**	37 ± 2	32 ± 2.0**a**	55 ± 2.4**a**	8.6 ± 1**a**
	LCF	**16**	22.2 ± 2.6	22.7 ± 1.4**a**	12.2 ± 0.8**a**	12.6 ± 1.3	0.4 ± 0.0**b**	3.5 ± 2.2**b**	56 ± 5.6**a**	32 ± 5	12 ± 6.4**b**	62 ± 7.4**a**	10.5 ± 0.6**a**
	P_Value	**242**	0.2008 ns	5.932e−11***	6.441e−12***	0.09342 ns	< 2.2e−16***	< 2.2e−16 * **	1.924e−06 * **	0.1552 ns	0.0006961 * **	0.002957 * *	0.256 ns
KANDI	**DIF**	**9**	26.2 ± 4.2**ab**	6.2 ± 2.1**b**	1.7 ± 1.3**b**	7 ± 2**b**	25.7 ± 2**a**	3.6 ± 1.4**b**	28.8 ± 6.7**b**	46.2 ± 5.7ab	25 ± 5	63.9 ± 11	5.5 ± 1.6**b**
	APF	**9**	33.2 ± 4.2**a**	5.6 ± 2.1**b**	1.9 ± 1.3**b**	8.9 ± 2**ab**	12.3 ± 2**b**	34.2 ± 1.6**a**	33.5 ± 6.7**b**	48.9 ± 5.7a	17.6 ± 5	47.3 ± 11	6.7 ± 1.6**ab**
	SCF	**48**	18.4 ± 1.8**b**	7.0 ± 1**b**	2.9 ± 0.6**b**	10.2 ± 1**ab**	1.8 ± 0.9**c**	2.4 ± 0.7**b**	43.0 ± 2.9**ab**	41.2 ± 2.4ab	15.8 ± 2	57.1 ± 5	8.3 ± 0.7**ab**
	LCF	**14**	20.9 ± 3.4**ab**	23.1 ± 1.7**a**	12.7 ± 1.**b**	13.8 ± 1.6**a**	0.45 ± 1.6**c**	3.2 ± 1.3**b**	57.6 ± 5.4**a**	29.4 ± 54.6b	13 ± 4	64.1 ± 9	11.6 ± 1.3**a**
	P_Value	**80**	0.008107 * *	< 2.2e−16 * **	< 2.2e−16 * **	0.01047 *	< 2.2e−16 * **	< 2.2e−16 * **	0.005327 * *	0.03348 *	0.3585 ns	0.6235 ns	0.02915 *
PEHUNCO	**DIF**	**8**	18.5 ± 3.2**ab**	6.1 ± 1.7**b**	1.1 ± 0.6**b**	11.6 ± 2	43.4 ± 1.9**a**	6.3 ± 4.5**b**	16.3 ± 7.5**ab**	23 ± 8	51 ± 10.2**ab**	31.8 ± 11	9.6 ± 1.4
	APF	**13**	25.1 ± 2.5**ab**	3.6 ± 1.4**b**	0.42 ± 0.4**b**	10.7 ± 1	2.4 ± 1.5**b**	40 ± 3.5**a**	4.2 ± 5.9**b**	31 ± 7	72.6 ± 8**a**	21.3 ± 8	8.9 ± 1.1
	SCF	**55**	15.3 ± 1.2**b**	7.6 ± 0.7**b**	1.8 ± 0.2**b**	9.5 ± 1	0.5 ± 0.7**b**	5.6 ± 1.7**b**	22.4 ± 2.8**ab**	32 ± 3	45.9 ± 3.8**ab**	40.2 ± 4	8.7 ± 0.5
	LCF	**2**	30.5 ± 6.5**a**	20.0 ± 1.8**a**	8.5 ± 1.2**a**	3.9 ± 4	0 ± 0**b**	5.2 ± 9**b**	42.5 ± 15**a**	50 ± 17	7.5 ± 20**b**	51.4 ± 21	3 ± 2.9
	P_Value	**78**	0.001951 * *	0.0004459 * **	4.535e−07 * **	0.2208 ns	< 2.2e−16 * **	1.292e−11 * **	0.0225 *	0.4295 ns	0.006103 * *	0.1901 ns	0.2541 ns
SAVALOU	**DIF**	**29**	17.4 ± 1.8**b**	4.3 ± 0.4	1.1 ± 0.3	8.2 ± 0.8	34.7 ± 1.6**a**	0 ± 1.2**b**	23.8 ± 4	45.2 ± 3	30.9 ± 3.5	61 ± 3.6**ab**	9.2 ± 0.5
	APF	**3**	26.3 ± 5.4**a**	7 ± 1.3	2.2 ± 0.8	7.8 ± 3	0 ± 5**b**	63.7 ± 3**a**	34.2 ± 12	45 ± 10	20.7 ± 11	40 ± 11.3**b**	6.6 ± 1.6
	SCF	**52**	19.3 ± 1.3**b**	4.78 ± 0.3	1.5 ± 0.2	8.1 ± 0.6	01.73 ± 1.2**b**	0.7 ± 0.7**b**	27.9 ± 3	40 ± 2	31.9 ± 3	69 ± 2.7**a**	8.7 ± 0.3
	P_Value	**84**	0.005788 * *	0.1218 ns	0.2512 ns	0.9892 ns	< 2.2e−16***	< 2.2e−16 * **	0.609 ns	0.3982 ns	0.6064 ns	0.01892 *	0.313 ns

* , * *, * **significant at 5 % (P < 0.05), ns not significant at (P ≥ 0.05). Values with the same letters are not significantly different. AE: Adult Equivalent. TLU: Total Livestock Unit.
DIF: Diversified Income Farm, **APF**: Agro pastoralist Farm, **SCF**: Small Cotton Farm, **LCF**: Large Cotton Farm.

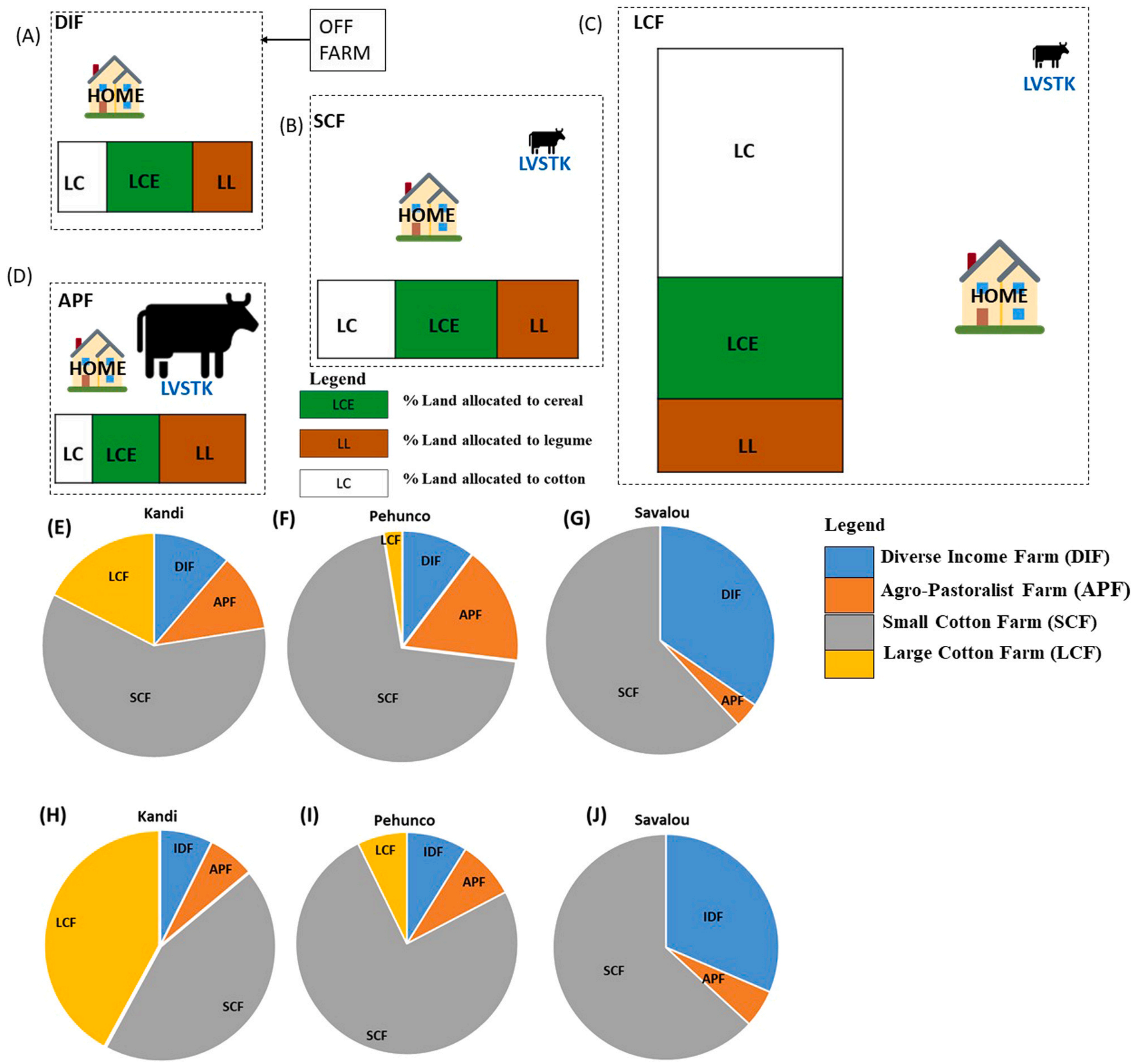

Fig. 2. Graphical models of farm types 1–4. The size of the components and boundaries of the system indicates their size and/or relative importance in reality (for example, the size delineated by the boundaries indicates the cultivated area). HOME: household (family size); LVSTK: livestock, the layout and size of each animal indicates its importance; OFF-FARM: external source of income. The pie charts E, F and G show the proportion of farm type across sites The pie charts H, I and J show the proportion of cultivated area per farm type across sites.

of 8.6 domestic employees who work full-time or part-time on farm activities.

- Type 2 (n = 25) = ***Agro-Pastoralists farms (APF)***: corresponds to the group of livestock farmers with an average of 40.7 TLU. 47 % of their cultivated area is dedicated to legumes, largely for livestock feeding (Fig. 2D), and 18 % of their land is cultivated to cotton. This reflects their dominant crop rotation type, which follows a cereal-legume-cereal pattern (Fig S4). They have the lowest average cultivated area (4.8 ha) and active household members (7.9). Around 5.7 % of household income is generated by off farm activities. They are thus less income diversified than DIF.
- Type 3 (n = 155) = ***Small Cotton Farms (SCF)***: this was the dominant type, grouping farms of medium size with an average of 6.5 ha of cultivated area including an average of 2 ha of cotton (Fig. 2B). They own a few heads of cattle (3 TLU), mostly oxen for ploughing. The cultivated area is evenly distributed between the different crops. This group has practically no off-farm income (1.3 %) and has the same average number of active household members (8.6) as the DIFs.
- Type 4 (n = 16) = ***Large cotton farms (LCF)***: These are large cotton farms with an average cultivated area of 23 ha. Cotton is the main crop on these farms, accounting for over 50 % of their cultivated area (Fig. 2C). Like SCF they have a few head of cattle (3 TLU) which are used to till the land and practice a cotton-cereal-cotton rotation, with 44.5 % for SCF and 87.5 % for LCF. Like small cotton farms, they depended strongly on farm income (off-farm income = 0.4 %) and have the largest number of household members (10.5).

Projection of the different farm types across the three sites revealed that SCFs were predominant in all three sites (Fig. 2E, F and G), LCFs were only present in the two northern sites (Kandi and Pehunco), DIFs were more common in Savalou (south) and APFs were more common in the two northern sites (Kandi and Pehunco). Despite the SCFs are the most representative farms in terms of numbers, they occupy the same proportion of cultivated area as LCFs in Kandi (Fig. 2H). In Pehunco, they occupy over 75 % of the cultivated area (Fig. 2I), while in Savalou they occupy over 60 %, followed by the DIFs who cultivate 31 % of the area in Savalou (Fig. 2J).

Although the four farm types were comparable in their structure and production orientation, they differed in their characteristics across the three sites (Table 5). For example, most farm types DIF and SCF in the south (Savalou) did not own cattle and cultivated less area than those in the north (Pehunco and Kandi) (respectively 4.3, 6.1, and 6.2 ha for DIFs) and (respectively 4.6, 7.6, and 7 ha SCFs). In addition, small cotton farms in the south produced less cotton than those in the north (respectively 1.5, 1.8 and 2.9 ha for Savalou, and Kandi) and sold more than 68 % of their cereal production. Specifically, Pehunco's income diversified farms accessed more off-farm income (43.4 %) and allocated more land to cereals than other sites. Agro pastoralists in the south (Savalou) owned more livestock (63.7 heads per farm) and cultivated a larger average area (7 ha) than those in the north, respectively 34.2 heads per farm and 5.6 ha on average at Kandi, and 40 heads per farms and 3.6 ha on average at Pehunco. Kandi's livestock owners exhibited higher proportion of off-farm income (12 %) than the overall average for this farm type (5.8 %), and those in Pehunco grew practically no cotton (0.42 ha). Only present in the north, Kandi's LCFs cultivated more total and cotton areas than those of Pehunco, respectively 23.1 and 12.7 ha (55 % cotton area share), versus 20 and 8.5 ha (43 % cotton).

3.2. Agricultural and management practices per farm type

Three tillage methods were identified in the study areas, mechanized tillage (12 %), tillage using animal traction (45 %) and manual tillage (43 %) (Fig. 3). Four main crop rotation types were identified: cotton//cereal (49.2 %), cereal/cotton//legume+coton (24 %), cereal//legume (19.8 %) and Legume/cereal//Cereal+cotton (7 %) (Fig S4). The tractor and moto-cultivator were used for mechanized tillage, while the hoe was used for manual tillage. As for animal-drawn tillage, pairs of well-trained and fit oxen were towed to ploughs to do the work. Mechanized tillage, which is not widespread in Benin, was mostly found at the Kandi and Pehunco sites. None of the farms belonging to the LCFs used manual tillage, whereas 80 %, 48 % and 60 % of the DIFs, SCFs and APFs did so respectively (Fig. 3A). Mechanized tillage was practiced by 31 % of LCFs and only 9 %, 14 % and 8 % of DIFs, SCFs and APFs respectively. Tillage with animal traction was practiced most by LCFs (75 %), while only 24 % of DIFs used this method. Tillage with animal traction was practiced by 53 % of SCFs and 44 % of APFs.

Analysis across sites reveals that no farm of any type used manual tillage in Kandi (Fig. 3B), while 99 % and 35 % of farms did so in Savalou (Fig. 3D) and Pehunco (Fig. 3C). Regarding crop rotations, 97 % of farm in Kandi grow maize after cotton (Fig S4 B) while 52.6 % do so in Pehunco. Since Savalou enjoys two rainy seasons a year, farmers are able to grow two crops on the same plot of land every year. Indeed, 57 % grow maize in the short season, followed by cotton in the first year and then legumes followed by cotton the following year. Furthermore, 20.2 % prefer to grow legumes followed by cereals and then cereals followed by cotton. All APFs and over 70 % of LCFs, SCFs and DIFs in Kandi used tillage with animal traction. Around 30 % of LCFs and DIFs in Kandi used mechanized tillage. At Pehunco, all three types of tillage were used, with all LCFs using tillage with animal traction, most DIFs and APFs using manual tillage, and around 30 % and 15 % respectively of SCFs and APFs using mechanized tillage. In Savalou, all farms, regardless of type, used manual ploughing. Only 3 % of DIFs used mechanized tillage.

Fig. 4 shows the frequency of different management practices associated with soil fertility maintenance per site and farm type. Across all sites (Fig. 4A), more than 80 % of all farm types practiced crop rotation. Over 80 % of all LCFs and APFs applied animal manure, while around 40 % of DIFs and MFs did it. About half of the APF and DIF practiced intercropping. Half of the APF corralled their animals on cropping plots by night and about 30 % of the LCF. Only about 6 % and 5 % of LCF and SCF respectively practiced no- or minimum tillage, and only 8 % of the APF produced fodder (generally legumes). However, such overall averages mask important variability within sites.

In Kandi, where there was a greater proportion of large, specialized cotton farms, the most common practices were crop rotation (cotton//maize) (Fig S4D) and animal manure applications (Fig. 4B). The nocturnal corralling of livestock herds on cropping parcels was restricted to a few of the LCFs (29 %) and SCFs (17 %). In Pehunco, crop rotation and manure application were also the most common practices but a relatively large proportion of APF, DIF and SCF farms practiced intercropping (Fig. 4C), predominantly of maize and cowpea or peanut,

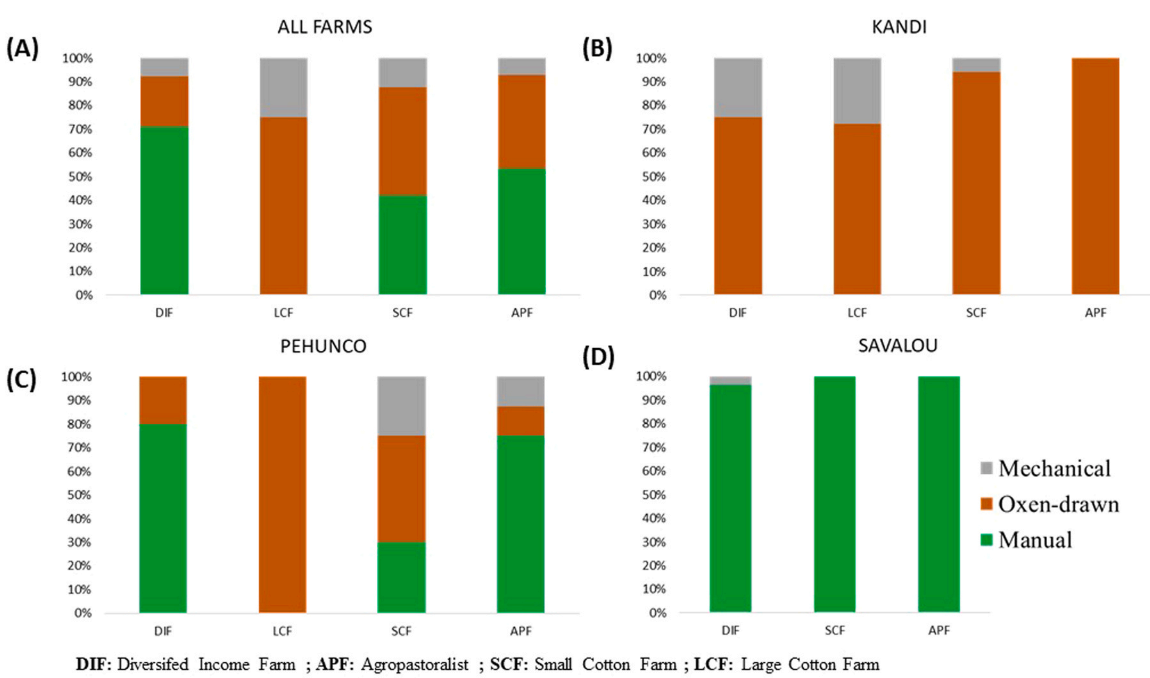

Fig. 3. Tillage methods by farm type (A) All farm, (B) Kandi, (C) Pehunco and (D) Savalou.

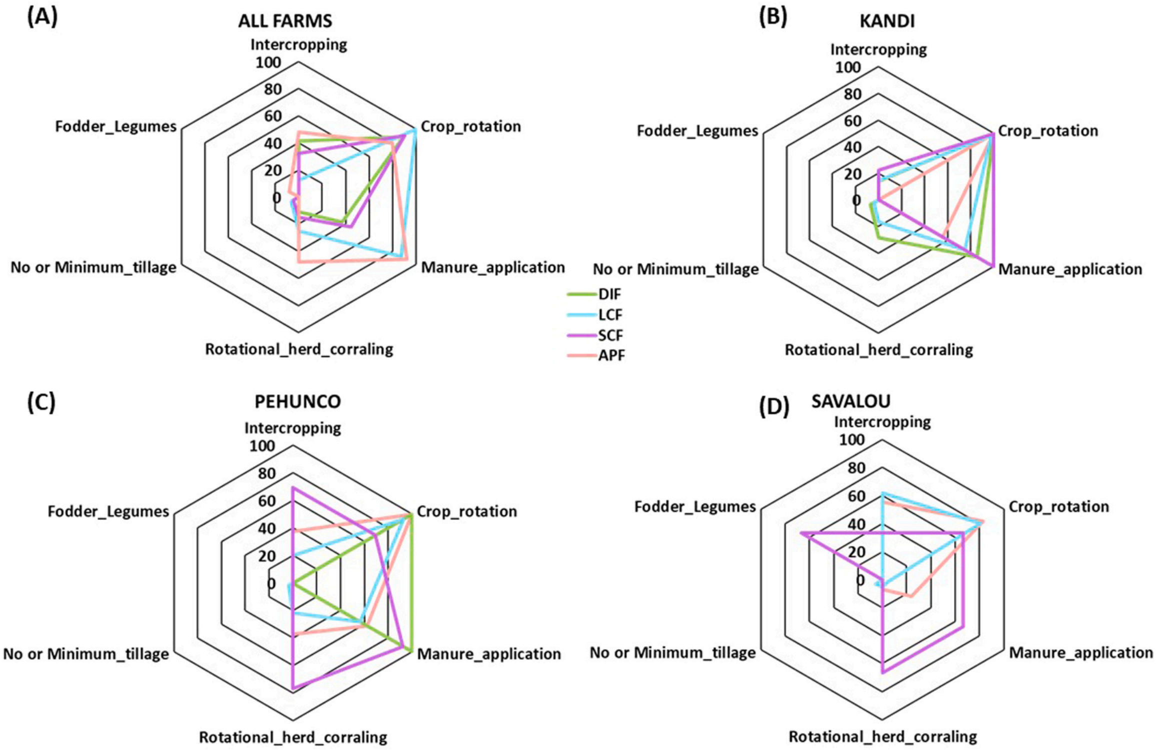

Fig. 4. Soil management practices by farm type (A) on all sites taken together, (B) in Kandi, (C)in Pehunco and (D) in Savalou; **DIF:** Diversifed Income Farm **; APF:** Agropastoralist Farm **; SCF:** Small Cotton Farm **; LCF:** Large Cotton Farm.

as well as livestock corralling on cropping plots. In Savalou, where farms were smaller and two crop growing seasons are possible (Fig. 4D), most APF farms produced legume fodder and all types practiced intercropping, while manure application was only restricted to APF farms. Despite having been amply promoted in Benin, no farm type practiced no-till or legume fodder production in Kandi and Pehunco, whereas only 2 % of the SCFs practiced no-till and 67 % of the APFs produced legume fodder in Savalou. Only 4 % of SCFs used minimum tillage on the three sites and 7 % of LCFs in Kandi.

3.3. Soil characteristics

3.3.1. Soil texture

Soil fractions were largely dominated by sand (70–90 %) in all soils sampled across the three sites while most soils had less than 20 % clay, resulting in a textural classification dominated by loamy sands and sandy loams, with a few loamy soils at Savalou and sandy soils at Kandi suppl. material). At Kandi and Savalou these two textures were found equally frequently distributed, whereas in Pehunco the sandy loam texture was dominant (Fig. 5A).

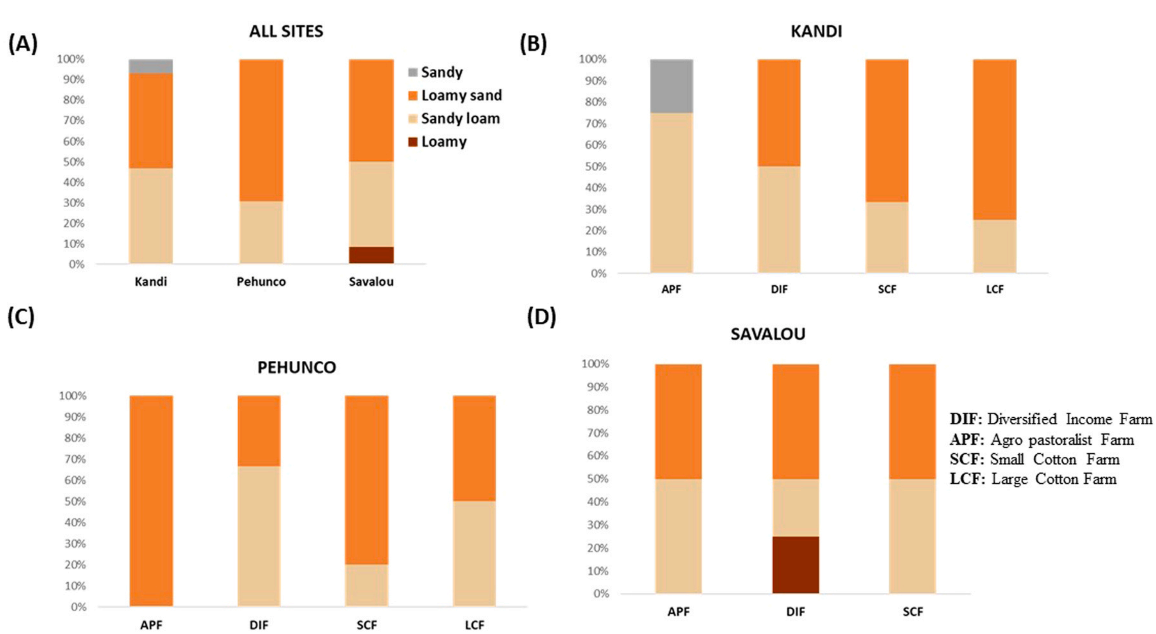

Fig. 5. Different soil textures per site and farm type. (A) on all sites taken together, (B) in Kandi, (C)in Pehunco and (D) in Savalou.

Analysis of soil textures by farm type across sites reveals additional variability, with sandy soils found only in the APFs (25 %) in Kandi (Fig. 5B), and loamy soils only in the DIFs (25 %) in Savalou (Fig. 5D). 100 % of the APFs in Pehunco (Fig. 5C) had sandy loam soils, whereas 50 % of the APFs in Savalou had the same type of soil. Half of the DIFs in Kandi and Savalou have sandy loam soils, while around 70 % of the DIFs in Pehunco have sandy loam soils. Most SCFs and LCFs on all sites have sandy loam soils. In Kandi and Pehunco, respectively 30 % and 20 % of SCFs have sandy loam soil, while 50 % of SCFs in Savalou have the same type of soil. For the LCFs, 25 % of the farms in Kandi have sandy loam soil and 50 % of them in Pehunco have the same soil texture.

3.3.2. Soil chemical characteristics

Soil fertility parameters varied from farm to farm. However, when considering the empirical soil fertility thresholds used in practice in Benin (cf. Table 4), almost all farms regardless of site or farm type had low to very low soil organic carbon contents (SOC$<$ 11.6 g kg^{-1}) (Fig. 6A) and very low levels of available phosphorus (P $<$ 10 mg/kg) (Fig. 6B). Soils at Kandi exhibited the lowest values for the five soil fertility indicators except exchangeable potassium (Fig S2 suppl. Material, Fig. 7), while Pehunco showed the highest variability and the highest values for all elements except exchangeable potassium. Soils in Savalou presented the highest value for exchangeable K. Most farms at Kandi (93 %) had very low values for SOC (SOC$<$ 5.8 g kg^{-1}) (Fig. 7B). Concerning total nitrogen, 87 % of farms in Kandi had very low values (total N $<$ 0.45 g kg^{-1}), while only 33 % of farms at Savalou were in this range. Pehunco's farms had low and good total N values and pH values slightly above 6.5 (the value above which pH can be a limitation to production), ranging from 6.61 to 7.51 (Fig. 7C). 60 % of Kandi farms had good pH values (between 5.5 and 6.5), while only 25 % of Savalou farms had such values.

From the 40 case study fields sampled, 32 were identified by farmers as 'non-fertile' and eight as 'fertile'. However, such categorisation of soil fertility based on farmers' perceptions did not always correspond with the observed values of soil indicators (Table 6). Fields perceived as fertile by farmers had indeed very low average values for all the soil indicators, except for exchangeable K at Kandi. At Pehunco, plots perceived as fertile had low average values for total N and exchangeable K and very low values for available P, while at Savalou they had low mean values for SOC and total N and very low values for P. Average value for most soil fertility indicators were comparable between fields perceived by farmers as fertile or poor, suggesting that farmers may consider a broader set of indicators beyond soil variables to regard a field as 'fertile'.

3.4. Farm types, management practices and soil fertility

The ANOVA on the five chemical parameters of soil fertility and the proportion of clay + silt revealed no significant differences between farm types at Kandi (Fig. 7) whatever the indicator. At Pehunco, there was a significant difference only for exchangeable K (Fig. 7F), while at Savalou differences were detected for available P (Fig. 7E). Although all farms had low values of available P, agro-pastoral farms showed the greatest variability and the highest average values at Kandi and Savalou, while at Pehunco, the DIFs showed the highest values and variability. The DIFs in Kandi and Pehunco as well as the SCFs in Savalou had the lowest clay and silt contents (Fig. 7A).

The APFs showed greater variability and higher values for SOC (Fig. 7B), total N (Fig D) and available P, while the LCFs showed greater variability and higher values for exchangeable K (Fig. 7F). Only 20 % of APF at Kandi had total N values greater than 0.04. Good levels of exchangeable K were found in half of the APFs and LCFs and in 25 % of the DIFs and SCFs (Fig. 7F). Soils in half of the farms of all types had pH values above 6.5 (Fig. 7C).

At Pehunco, the large cotton farms had the lowest values for all parameters except exchangeable K, while the SCFs had the highest values for SOC and total nitrogen (Fig. 7B and D). All APFs and 33 % of SCFs had very low values for exchangeable K (Fig. 7F). Most APFs, LCFs and SCFs have average SOC values (between 5.8 and 11.6 g kg^{-1}) except for DIFs, which had higher values (SOC $>$ 11.6 g kg^{-1}). Respectively, 67 %, 33 %, 67 % of APFs, DIFs and SCFs had very good total N content (above 0.8 g kg^{-1}). Although all farm types had pH values favourable to cotton production according to the empirical thresholds used in Benin, the DIFs had more adequate soil acidity (Fig. 7C).

At Savalou, the DIFs had the highest SOC values (Fig. 7B et D) between 5.8 and 11.6 g kg^{-1}. For total N, most farms regardless of type, had average values between 0.4 and 0.8 g kg^{-1} (Fig. 7D). The SCFs had the highest values of exchangeable K, unlike the APFs, which had the lowest K exchangeable values for this site. Soils in some farms belonging to the APFs (50 %) and all DIFs had pH values below 6.5 (Fig. 7C).

No clear link was detected between farm types, soil management practices and soil fertility levels through the indicators measured here. This is illustrated for soil organic carbon in Fig. 8, where fields were categorized as having very low (35 % of the plots), low (47 % of the plots) or good (18 % of the plots) carbon contents following the empirical thresholds used in Benin (cf. Table 4). Similar patterns as those observed for SOC were observed for the other soil fertility indicators. The absence of clear links may point to other soil fertility factors that have not been addressed in this study (e.g. soil compaction). Respectively 18 %, 50 % and 19 % of all fields with crop rotation, intercropping and manure application exhibited good SOC levels (Fig. 8). However, 38 %, 35 %, 33 % and 22 % respectively of the fields with crop rotation, manure application, no or minimum tillage and rotational herd corralling had very low SOC levels. Fields that received animal manure, mineral fertilizers, or both combined, present SOC levels that may correspond to the categories very low, low or good

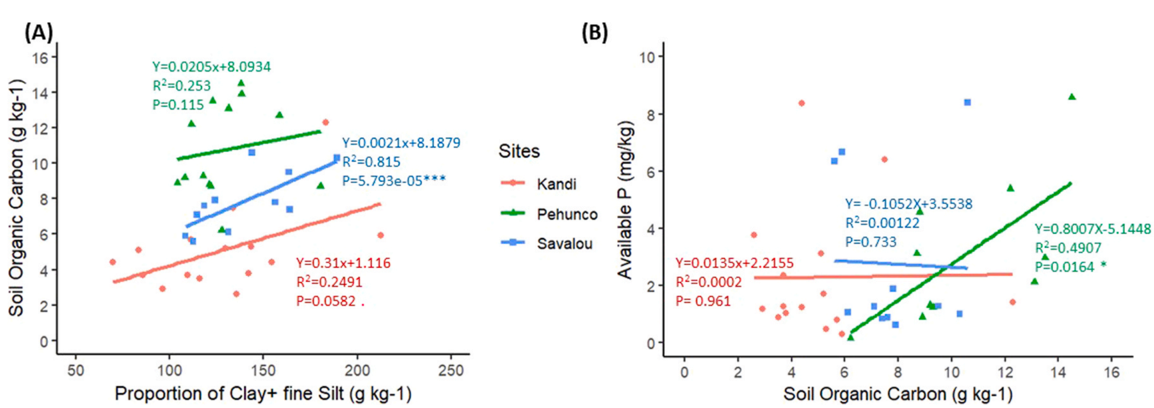

Fig. 6. Variability of soil organic carbon with (A) the proportion of clay + silt and (B) available phosphorus and with soil organic carbon. Trend analysis was carried out on all the data except Pehunco, where 2 outliers were eliminated.

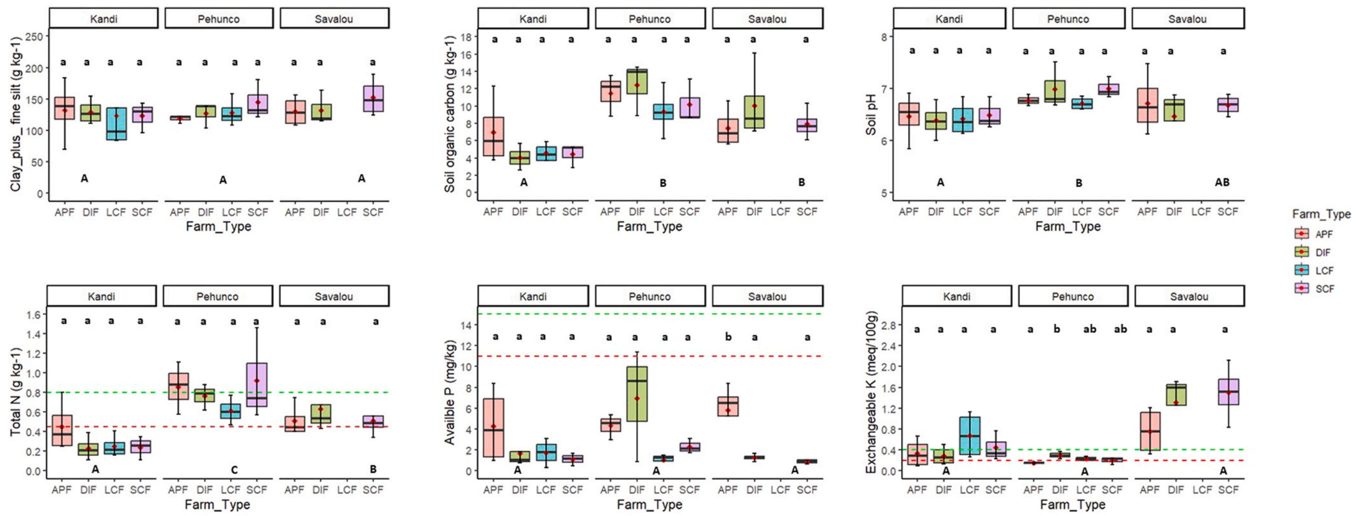

Fig. 7. Chemical characteristics and clay + Silt of farm soils by Farm type into sites. **Red line**: Value below which the element presents a severe limitation for soil production. **Green line**: Value above which the element presents no limitation for soil production, Box plots with the same letters are not significantly different at 5 % (P ≥ 0.05), however, miniscule letters show the difference between farm types within a site and majuscule letters show the difference between sites.; The mean value is compared by type within the site; **DIF:** Diversified Income Farm**; APF:** Agro pastoralist Farm**; SCF:** Small Cotton Farm**; LCF:** Large Cotton.

Table 6
Fertility class according to farmers versus soil data.

Sites	Farmers soil fertility class	N	Clay + Silt content (g kg^{-1})	Soil organic carbon (g kg^{-1})	Total N (g kg-1)	Extractable P (mg kg-1)	Exchangeable K (cmol (+)	pH (water 1:1.25)
Kandi	Fertile	2	76.7 (NA)	4.8 (0.3–9.2)	0.25 (0.25–0.25)	5.75 (NA)	0.21(NA)	6.40 (3.15–9.64)
	Poor	13	135 (114−156)	5.1(3.6–6.67)	0.30(0.2–0.42)	1.75 (0.75–2.75)	0.47(0.27–0.67)	6.45 (6.24–6.65)
Pehunco	Fertile	1	158 (NA)	13.9 (NA)	0.77 (NA)	1.52 (NA)	0.28 (NA)	6.86 (NA)
	Poor	12	127 (114−140)	10.9 (9.2–12.6)	0.78 (0.60–0.95)	3.62 (1.47–5.77)	0.22 (0.17–0.26)	6.86 (6.69–7.03)
Savalou	Fertile	5	191 (0.284–381)	9.2 (3.8–14.6)	0.62 (0.28–0.95)	4.74 (0.54–8.94)	1.16 (0.18–2.14)	6.59 (5.69–7.7.49)
	Poor	7	148 (123−174)	7.9 (6.6–9.3)	0.51 (0.39–0.62)	1.18 (0.85–1.50)	1.22 (0.77–1.66)	6.65 (6.49–6.81)

NB: See Table 4 **for assessment criteria per indicator.**

according Benin's empirical thresholds. Similarly, fields in which crop rotation and herd corralling were practiced fell also within any of these three categories. The few fields where intercropping, legume fodder production or minimum tillage were practiced fell within the intermediate to higher SOC categories. Further, cotton yield levels were not intrinsically linked to either farm type or SOC level (Fig S6).

4. Discussion

The use of a multi-scale approach combining a statistical typology and targeted soil analyses enabled us to understand the variability of fertility in three representative cotton growing areas of Benin and identify some levers for optimizing farming practices. The analysis of 242 smallholder farms allowed identifying four main farm types based on resource endowment and production orientation. Although these farm types differed in their management practices, notably in their access to animal manure and mechanization, there was no strong association between farm type and soil fertility status. Contrasting average soil fertility indicators against recommended thresholds for cotton in Benin (cf. Table 4) revealed that diversified and agro-pastoral farms tended to exhibit average soil fertility levels within or above the recommended range, except for available P which was low to extremely low in all soils (cf. Fig. 7). In small and large cotton growing farms, in which respectively more than 30 and 50 % of the area is allocated to cotton, and where hence mineral fertilizers are applied every year (Fig S5), soil fertility status was generally below the recommended range. The following sections discuss possible reasons behind these patterns and their implications for reversing soil fertility decline in Benin cotton growing areas.

4.1. Farm typology

The farm categorisation proposed was based on their most common structural characteristics, such as instant inventories of endowments and income (land use, proportion of land under cotton, livestock, income) as done by e.g. Berre et al. (2022) and Kuivanen et al. ((2016), but based also on their dependence on off-farm income (e.g., Tittonell et al., 2005). Whereas large cotton farms were only present in the northern sites, the other three farm types were consistent across sites, with slight differences among farms of the same type at different sites, as found by Awoke Eshetae et al. (2024). This intra-type diversity can be explained by differences in the production system and socio-cultural characteristics of the three sites. In the north of Benin, animal-drawn ploughing is the most widespread method of soil tilling (Fig. 3), so owning animals is crucial to various farming activities. This is not the case in the smaller farms of the south, where tilling is done manually and cultivation areas are smaller. Such intra-type diversity does not question the validity of the typology but, on the contrary, confirms that a typology is closely linked to the objectives pursued and the criteria used to group the farms together (Alvarez et al., 2018). Agropastoral farms in the south had

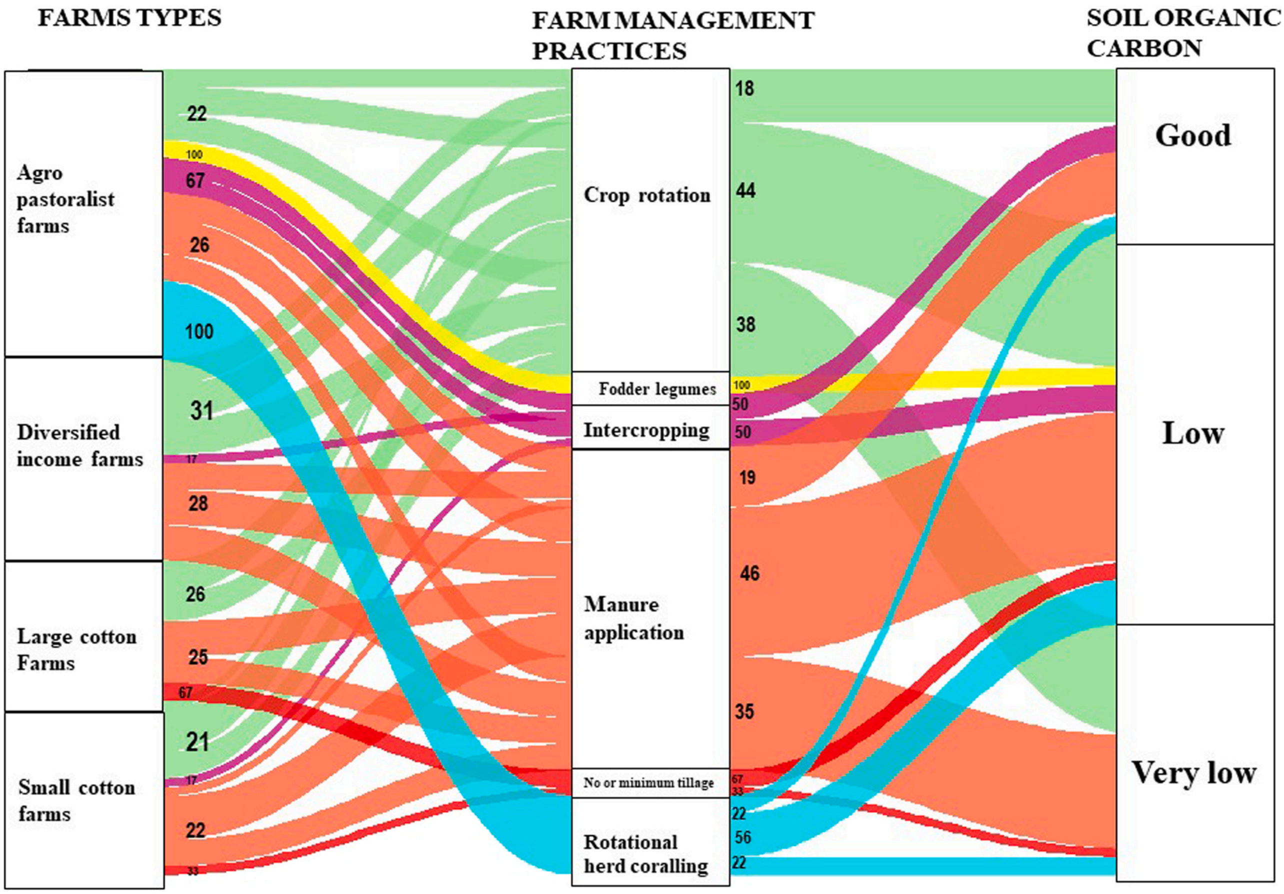

Fig. 8. Link between farm types, management practices and SOC; frequency is calculated for the farm type-practices and practices-SOC level links. Good: (SOC > 11.6 g kg^{-1}), Low: 5,8≤SOC≤11,6 g kg-1), very low SOC< 5.8.

larger herds than those in the north, a trend that has been increasingly observed in recent years and that is associated with climate warming and the reduction in natural fodder for animals in the north of the country (Dossouhoui et al., 2023). The scarcity of fodder during the dry season, combined with the Law on Sedentarization of Pastoral Peoples in Benin (Government of Benin, 2021), has led herders in the north to reduce their herds. Continuously changing availability of grazing lands and water resources are the main drivers of the transformation in the pastoral systems (Houessou et al., 2019). The 'sedentarisation' of pastoralists has led to a privatisation of animal manure, a resource that was more easily accessed by all types of farms, even those without livestock, in the past (Dossouhoui et al., 2023). Cotton farms (SCFs, LCFs), on the other hand, strongly rely on farm income, which makes them more vulnerable to the vagaries of climate (Omotoso et al., 2023), price fluctuations, and the political decisions taken on the cotton sector in Benin (Maboudou Alidou and Niehof, 2020).

4.2. Is farm type determining soil management practices?

The results indicate that the implementation of a given management practice was determined by the resources available on the farm, as shown in Benin by Tovihoudji et al. (2024) and Ngaiwi et al. (2023). In general, the practices most widely adopted in the study area were crop rotation with cotton/maize leading in all farm types except DIFs, where it was cotton/cereal/legume/cotton (Fig S4), followed by manure application and intercropping. Manure application was more common among the large cotton and agropastoral farmers, whereas rotational herd corralling was almost restricted to the latter. Agro-pastoralists, with their large livestock herds have the easiest access to manure, which explains their capacity to implement this practice. When pastoralism was mostly nomad or transhumant, cotton farmers and pastoralists would reach agreements for night corralling on cropping fields, allowing high inputs of animal manure concentrated in small areas. This practice is however disappearing as mentioned earlier (cf Dossouhoui et al., 2023). Manure application is often also limited by labour availability (Diarisso et al., 2015). Large cotton farms, with their greater labour power in terms of the number of workers per household (Table S1), are better able to transport manure produced by their livestock to cropping fields.

Intercropping was most widely adopted by smaller farms (DIFs, SCFs, and APFs) in Pehunco and Savalou, with a strong representation in the latter. Benefiting from two rainy seasons, they intercrop maize and cowpea during the first season before producing cotton or soybean in the second season. These crop choices, guided by the yield and sale price of the crop in the previous year, are a subsistence strategy for these farmers (Yegbemey, 2021). It allows farmers to have a varied stock of foodstuffs in the first rainy season and cereals to sell to support production expenses in the second rainy season. Intercropping was practically nil on large (mechanised) farms. Other practices that are encouraged in West Africa, such as minimum or no tillage, ploughing crop residues in the soil before sowing, sowing under plant cover (Akplo et al., 2025, 2024) and producing fodder legumes, were hardly observed in the 242 households interviewed as part of this research. The choice of practices at farm level was mainly motivated by the resources already available to farmers in their context (Sui and Gao, 2023; Issahaku and Abdulai, 2020) and was only partially aligned with farm types (cf. Fig. 4). Particularly on cotton-growing farms (LCF and SCF) we observed that practices using crop harvest residues, such as their incorporation into the soil before sowing, or direct sowing under plant cover, were not practiced by farmers. This may be due to the pressure exerted by livestock on crop residues in these regions and the additional labour required by these practices. In fact, in the study area, after harvesting, crop residues are grazed by free marauding herds. This leads to conflicts between farmers and livestock owners. Action must therefore be taken at territory scale to reduce the pressure on crop residues so that they can be utilized for soil fertility maintenance, without compromising the livestock feed needs (Andrieu et al., 2015).

4.3. How do soil management practices influence soil fertility?

No clear link could be detected in this study between management practices and current soil fertility levels, as illustrated in Fig. 8 for soil organic carbon. These results are contrasting with those reported by a large body of scientific literature published about twenty years ago, which showed a strong link between soil management practices and soil fertility status throughout sub-Saharan Africa (e.g., Zingore et al., 2007; Tittonell et al., 2005; Samaké et al., 2005; Carter and Murwira, 1995). These studies placed emphasis on the heterogeneity of soils within farms, highlighting the existence of zones of soil fertility depletion and accumulation within the same farm. In the present study, soils were purposively sampled by asking farmers to identify poor and fertile soils in their fields, irrespective of their location on the farm (cf. Table 6). These fields were generally not contiguous and were scattered across the landscape, often at great distances from each other. Although a wide variation was observed in soil chemical parameters between fields and farms, these could not be ascribed to spatial variation or to farmers' perception of soil fertility.

The range of variation of key soil fertility attributes differed for each farm type, based on resource endowments and soil management practices, but also largely across the three sites (cf. Fig. 7), indicating a stronger influence of soil textural characteristics (cf. Fig. 6) and climatic conditions. Management-induced differences in SOC were less pronounced in this study than in the finer textured soils in humid climates of the East African highlands (Wanjiku Kamau et al., 2019; Willy et al., 2019). Soil response to management practices in cotton based cropping systems in our study areas may be more perceptible in crop responses (crop yield) than in soil physicochemical properties. This was shown in several long-term studies in West Africa. For example, Ripoche et al. (2015) report a long-term experiment (25 years) in Mali in which organic and mineral fertilisers and their combination led to stronger differences in crop yields, especially with combined fertiliser and manure, than in soil nutrient levels (SOC, N, P, K). Similarly, treatments that combined different levels of fertiliser use with or without crop residue incorporation in the soil in comparable agroecosystems of neighbouring Togo led to stronger variability in crop yield than in soil properties, which significantly declined in all treatments after 15 years (Kintché et al., 2015).

In addition the degree to which manure affects the soil depends on the physical and chemical properties of the manure itself and on various management and environmental factors, including the rate and timing of application, application method, soil type and climate (Rayne and Aula, 2020). In the study area, manure is not incorporated into the soil but is exposed to extremely hot temperatures and rainfall, which affects its quality, as shown in different studies (Castellanos-Navarrete et al., 2015; Rufino et al., 2007). This practice, combined with the sandy texture of the soil, does not facilitate a positive response to manure additions. Samson et al. (2020) found that that manure had a pronounced effect on microbial biomass, leading to the accumulation of microbial amino sugar and SOC, only in a silty clay soil. However, they also found residue conservation were particularly effective at increasing surface SOC content and crops yield, independently of soil texture. The positive effect of crop diversification (Crop rotation and intercropping) on SOC depends not only on soil properties but also on the species used (Li et al., 2024). SOC accumulation in intercrops is affected by crop residue composition and regulated by the soil C/N ratio, particularly in soils with low nitrogen content like the soils in our study areas. This highlights the crucial role of crop residue management and diversification practices in improving SOC stocks and maintaining productivity in the cotton-growing areas of Benin. However, the widespread practice of uncontrolled grazing remains a major obstacle to the adoption of these practices. In this context, targeted actions are needed at several levels to facilitate the implementation of residue-based soil management strategies.

More specifically, we recommend that Beninese policy-makers develop context-specific land-use regulations and incentives to increase fodder production and promote the recycling of crop residues for soil use or facilitate a win-win partnership between cotton farmers and livestock owners to guarantee the return of manure after biomass removal by livestock, especially in the current context of promoting sedentarization. Researchers should give priority to studies that explore the biophysical and socio-economic trade-offs associated with the use of crops residues in mixed crop-livestock systems. At the same time, development agency need to work directly with farmers through participatory approaches to co-develop and roll out context-specific solutions on a large scale. Strengthening local innovation systems and promoting dialogue between farmers and livestock breeders will be essential if soil fertility objectives are to be reconciled with livestock feed requirements in these agroecosystems.

4.4. Soil chemical characteristics across sites and farm types

Soils in the case study fields in Pehunco had the highest SOC and N values, followed by those at Savalou and Kandi. This difference can be attributed to the specific soil and climatic conditions in each region. Pehunco, with greater rainfall and lower temperatures than Kandi (Table 1) may benefit from slower mineralization of carbon and nitrogen (Bationo et al., 2007; Six et al., 2002). Conversely, the degradation of soil organic matter could be accelerated in Kandi, under drier conditions and greater agricultural pressure, leading to a decrease in SOC and total N. Soils in Pehunco are more clayey than those in Kandi and Savalou (Fig. 5A), which may better protect organic matter from microbial decomposition (Dignac et al., 2017). Pressure on agricultural land and the intensity of agricultural practices are greater in Kandi than in Savalou and Pehunco, as evidenced by the extent of the cultivated area and agricultural production (DSA, 2024). All these factors could limit the soil's capacity to accumulate C and N (Bationo et al., 2007; Six et al., 2002). Nevertheless, most soils across the four farm types in the three sites exhibited low to very low values for all the chemical parameters studied, according to local references (Dabin, 1956; Igue et al., 2013; Landon, 2013), with the exception of exchangeable K. The situation is critical when it comes to available P, for which values were very low on all case study fields. These results are in line with the study by Amonmide et al., (2019) which found similar patterns in the same study area. It is striking that areas dedicated to such an important cash crop as cotton, exhibit such low levels of soil fertility. Unlike other regions of sub-Saharan Africa, where only a small proportion of farmers use small amounts of mineral fertilisers (e.g., Jambo et al., 2019;Castellanos-Navarrete et al., 2015; Baudron et al., 2012; Zingore et al., 2011), farmers in cotton growing regions of Benin receive fertilisers and other chemical inputs annually through contract farming. The claim that soil fertility can be maintained with mineral fertilisers, already debunked years ago by long term studies in West Africa (e.g. Ripoche et al., 2015; Kintché et al., 2015, 2010; Guibert, 1999) but still persistent in the international arena (e.g., Dimkpa et al., 2023; Holden, 2018), is further refuted by the results of the present study. Evidence on the positive effect of associating mineral fertilizers with organic manure on long term soil productivity is often presented, especially for cereal crops on inherently richer soils (Laub et al., 2023; Gram et al., 2020), but less so for cotton cropping systems in the savannah-derived soils of west Africa.

In our study, agro-pastoralists (APF) exhibited the highest values in SOC and N values in their fields, whereas large cotton farms showed the lowest (Fig. S3). This indicates that the integration of agriculture and livestock may promote greater inputs of organic matter to soil via animal excreta (Sekaran et al., 2021; Rayne and Aula, 2020). Yet fields in which livestock night corralling was practiced had also very low and low values of soil fertility indicators (cf. Fig. 8). In contrast, fields in large cotton farms, although benefiting from higher inputs of chemical fertilisers through cotton cultivation, may be subject to accelerated carbon mineralization due to a low return of organic residues and the climatic characteristics of their predominant area in Kandi. Crop-livestock integration could be an effective strategy for maintaining or improving soil fertility and crop yields in Benin, particularly by increasing organic matter inputs. However, the effectiveness of this approach depends on manure management (quantity, quality and method of application), which remains a major constraint in West Africa (Ntamwira et al., 2023; Vall et al., 2023; Paracchini et al., 2020; Ndambi et al., 2019). The difference observed between farm types highlights the importance of considering the diversity of farms in soil management recommendations (Berre et al., 2022). A single approach would not be suitable for all farm types, and a combination of practices adapted to each production system would be more effective at improving soil sustainability in the cotton-growing areas of Benin.

4.5. Limitations of the study, recommendations and way forward

Soil fertility decline can be assessed using a set of properties obtained at different periods on the same site or in different land use systems with the same soils at a given time. The former is often used to evaluate technologies and is easy to interpret, while the latter is used to assess the state of the soil at a given time, with the obvious advantage of collecting data more quickly (Hartemink, 2006). In our study we used the second approach and soil samples were taken from the same cropping system (cotton-based), from different farm types, on the most dominant soil types, and following farmers' perception of soil fertility. This resulted in a representative sampling, given the small variation in soil textures across the three areas (all coarse textured soils). However, the status of soil fertility assessed in this study is supported by soil analysis data from 40 fields, a minimum sample size to capture these sources of variation (farm type/management, climate, field sizes and their location on the landscape). In further studies, we recommend increasing sampling sizes using regular grids to allow testing for spatial correlation through geostatistics e.g (Tittonell et al., 2008), and increasing the frequency of sampling by calibrating wet-chemistry soil data against near-infrared reflectance spectra (NIRS), resulting in quicker and more affordable soil testing (Johnson et al., 2021; Tittonell et al., 2008).

In sandy soils, an important fraction of the available phosphorus content varies with the organic matter content of the soil (cf. Fig. 5). SOC enables organically held nutrients to be released through mineralization by micro-organisms. Enriching the soil with organic matter increases the contribution of organic P to overall P dynamics, improves soil pH, and provides additional N (Lal, 2021). The surest way to improve soil fertility in the Benin cotton zone appears to be through improving soil organic matter content. As animal manure is limited only to livestock owners or better resource endowed farmers, other means to restore soil organic matter are needed. Tillage influences the quantity and composition of soil organic matter (Šimon et al., 2009) and has an impact on soil structure, water infiltration and soil porosity (Farahani et al., 2022; Blanco-Canqui and Ruis, 2018). The tillage methods most widely adopted in the study area, manual and harnessed tillage (Fig. 3), consist of turning over the soil, often to a depth of more than 15 cm. This leads to periodic disruption of the soil structure, exposing organic matter physically protected in micro aggregates to biodegradation and oxidation, threatening the soil microfauna responsible for mineralizing organic matter, and encouraging evapotranspiration and volatilisation of nitrogen (Dassou et al., 2024). Reducing intensive tillage to a minimum, covering the soil and applying organic matter (crop residues, cover crops and animal manure) annually at the right rates and producing fodder crops to minimize competition for crop residues, appear as key practices to sustainably improve soil fertility in the cotton-growing zones of Benin. However, implementing simultaneously zero tillage and total cover known as conservation agriculture in sub-Saharan Africa comes up against numerous constraints, such as inadequate soil cover, weed pressure, specific mechanization and low fertilizer inputs. To cope with these various constraints, strategies have been designed to overcome the main challenges faced by smallholder farmers adopting CA, namely the availability of plant biomass and minimum tillage which is designed as an intermediate step in the transition toward Conservation Agriculture (CA). Plant biomass production through cover crops (which are also of food interest in the area such as forage cowpea), crop residues and/or manure appear to be major elements for ensuring additional benefits in the subsoil in some case (Kassam et al., 2020; Nezomba et al., 2017). Furthermore, this biomass of cover crops can also serve as forage for livestock during the dry season, reducing competition for crop residues (Tittonell et al., 2015) The second strategy is the minimum tillage (instead of no-tillage), which disturbes only 20 % of the soil surface while keeping the inter-row undisturbed and mulched (Yemadje et al., 2022). The authors concluded that minimum tillage and/or biomass incorporation (cover crops, crops residues and manure) appear to be a wise approach to initiate a transition toward more sustainable soil management. Given the current change from transhumant to sedentary livestock herding in Benin, the promotion of fodder production for livestock by the project leading this policy (MAEP, 2021) could be the start of a solution, as it could reduce competition between soil and livestock for crop residues.

4.6. Lessons learnt and recommendations

From our multi-scale analysis, we found that, despite the consistency of farm typologies across sites, the expected links between management practices and soil fertility levels were weak or absent. This highlights the complexity of soil fertility dynamics, influenced not only by reported farming practices, but also by land-use history, climatic variability and intrinsic soil properties. Agricultural practices implemented depend on the availability of resources at farm and/or terroir level. Crop residue management at terroir level is therefore a key factor in soil fertility dynamics. The export or poor valorisation of agricultural biomass reduces the organic restitution to soils and accelerates their impoverishment, even in the presence of mineral inputs. Furthermore, the way in which soil management practices are implemented by farmers strongly influences their actual effectiveness. Local adaptations, resource constraints and farm priorities largely determine the success or failure of recommended practices. It is also important to remember, in the light of Liebig's law of the minimum, that soil fertility is conditioned by the most limiting nutrient: even if several practices are well applied, the presence of a single deficient factor (such as a deficit in organic matter or a key mineral element) can limit production and mask the positive effects of the practices implemented. So, to strengthen the assessment and sustainable management of soil fertility in the future through a multi-scale approach, we suggest:

1-Integrate long-term monitoring of biological soil indicators (e.g. microbial biomass, soil respiration), to complement physico-chemical analyses;

2-Integrate agricultural yield assessment, taking into account input levels, as a complementary functional indicator of effective soil fertility. Yield would thus provide a better understanding of the real capacity of soils to support agricultural production under actual farm management conditions, in accordance with Liebig's law of the limiting factor.

3-Take better account of landscape-scale factors (erosion, topography, biomass flows) using spatial analysis tools (GIS, remote sensing) and participatory approaches (participatory mapping, serious game);

4-Include farmers and other key stakeholders of the territory via participatory approaches to document the actual implementation of practices, integrate local knowledge and better understand contextual constraints;

5-Develop dynamic, participatory models articulating the interactions between socio-economic drivers (access to resources, collective organization of residue management) and biophysical processes, notably by integrating serious games as social learning devices to stimulate collective reflection, foster knowledge exchange between farmers, researchers and advisors, and co-construct more robust strategies for sustainable soil fertility management.

These approaches would enable the production of better contextualized and more operational knowledge, useful for both the scientific community and cotton industry stakeholders, in order to build sustainable soil management strategies that are effective, equitable, and adapted to territory's realities.

5. Conclusion

The multi-scale approach used in this study has enabled a first approximation to understanding the complex interactions between farm types, management practices and soil physicochemical characteristics across sites. Farms in three major cotton growing zones of Benin showed coherent diversity patterns, as revealed by typologies that were created according to resource endowment, income sources and production orientation. Among the four farm types identified, two specialised in cotton growing, one was livestock-oriented type and one diversified. This study highlighted the dependence of farmers' choices for soil management practices based on farm resources. However, our major findings regarding soil fertility status were:

(i) a generalised poor level of soil fertility, as measured by classical soil physicochemical properties, in case study fields that receive annual inputs of mineral fertilisers across farm types and sites;

(ii) no clear links between the management practices implemented by different farm types and soil fertility levels.

In other words, fields subject to a certain type of management (e.g. manure application, night corralling of livestock, crop rotation) exhibited either good, low or very low soil fertility levels, according to Benin's empirical soil quality thresholds. This can be partly explained by the edapho climatic conditions of Benin's cotton regions, dominated by coarse-textured soils and extreme high temperatures and by inappropriate soil management practices such as uncontrolled free grazing of livestock, intensive soil tillage. In different regions in our study, traditional pastoral systems are extensive, and based on the seasonal utilization of large grazing areas at village scale. All farms were exposed to grazing. Our findings further indicate that such a multiscale approach allows assessing soil fertility with a relatively limited number of soil samples, and categorising its diversity in a way that can inform innovation targeting across farm types and sites to improve the feasibility and adoption of sustainable soil management practices.

Author's contribution

Anita DOSSOUHOUI collected, analysed, edited the data and wrote manuscript. Pierrot Lionel Yemadje contributed to improve the manuscript. David Berre participated in data analysis and manuscript improvement. Rodrigue Vivien Cao Diogo contributed to improve the manuscript. Pablo Tittonell supervised the research, contributed to the design and structure of the article and co-edited the manuscript. All authors contributed to this article and approved the submitted version.

CRediT authorship contribution statement

Dossouhoui Anita: Writing – original draft, Methodology, Formal analysis, Data curation. **Pierrot Lionel Yemadje:** Writing – review & editing. **David Berre:** Writing – review & editing, Formal analysis. **Rodrigue Vivien Cao Diogo:** Writing – review & editing. **Pablo Tittonell:** Writing – review & editing, Supervision, Conceptualization.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109749.

Data availability

Data will be made available on request.

References

Abera, A., Yirgu, T., Uncha, A., 2021. Determinants of rural livelihood diversification strategies among Chewaka resettlers' communities of southwestern Ethiopia. Agric. Food Secur 10, 30. https://doi.org/10.1186/s40066-021-00305-w.

Akplo, T.M., Kouelo Alladassi, F., Zoundji, M.C.C., Fulajtar, E., Benmansour, M., Rabesiranana, N., Akinseye, F.M., Houngnandan, P., 2024. Effect of no-tillage on soil redistribution estimated by beryllium-7, soil moisture, and carbon fractions loss in central Benin. Agrosystems Geosci. Environ. 7, e20452. https://doi.org/10.1002/agg2.20452.

Akplo, T.M., Yemadje, P.L., Imorou, L., Sanni, B., Boulakia, S., Sekloka, E., Tittonell, P., 2025. Minimum tillage reduces variability and economic risks in cotton-maize rotations in Northern Benin. Field Crops Res. 324, 109795. https://doi.org/10.1016/j.fcr.2025.109795.

Alary, V., Messad, S., Taché, C., Tillard, E., 2002. Approche de la diversité des systèmes d'élevage laitiers à la Réunion. Rev. D. 'élevage Médecine V. ét. Pays Trop. 55, 285. https://doi.org/10.19182/remvt.9816.

Alvarez, S., Paas, W., Descheemaeker, K., Tittonell, P.A., Groot, J.C., 2014. Typology construction, a way of dealing with farm diversity: general guidelines for Humidtropics. CGIAR Res. Program Led. IITA 1–37.

Alvarez, S., Timler, C.J., Michalscheck, M., Paas, W., Descheemaeker, K., Tittonell, P., Andersson, J.A., Groot, J.C.J., 2018. Capturing farm diversity with hypothesis-based typologies: an innovative methodological framework for farming system typology development. PLOS ONE 13. https://doi.org/10.1371/journal.pone.0194757.

Amonmide, I., Dagbenonbakin, G., Agbangba, C.E., Akponikpe, P., 2019. Contribution à l'évaluation du niveau de fertilité des sols dans les systèmes de culture à base du coton au Bénin. Int. J. Biol. Chem. Sci. 13, 1846–1860. https://doi.org/10.4314/ijbcs.v13i3.52.

Andrieu, N., Vayssières, J., Corbeels, M., Blanchard, M., Vall, E., Tittonell, P., 2015. From farm scale synergies to village scale trade-offs: cereal crop residues use in an agro-pastoral system of the Sudanian zone of Burkina Faso. Agric. Syst. 134, 84–96. https://doi.org/10.1016/j.agsy.2014.08.012.

Asaaga, F.A., Hirons, M.A., Malhi, Y., 2020. Questioning the link between tenure security and sustainable land management in cocoa landscapes in Ghana. World Dev. 130. https://doi.org/10.1016/j.worlddev.2020.104913.

Assogba, G.G.C., Adam, M., Berre, D., Descheemaeker, K., 2022. Managing biomass in semi-arid Burkina Faso: Strategies and levers for better crop and livestock production in contrasted farm systems. Agric. Syst. 201. https://doi.org/10.1016/j.agsy.2022.103458.

Awoke Eshetae, M., Abera, W., Tamene, L., Mulatu, K., Tesfaye, A., 2024. Understanding farm typology for targeting agricultural development in mixed crop-livestock farming systems of Ethiopia. Farming Syst. 2. https://doi.org/10.1016/j.farsys.2024.100088.

Azontondé, H.A., Igué, A.M., Dagbénonbakin, G., 2016. La carte de fertilité des sols du Bénin par zone agroécologique du Bénin. Document validé à l'INFOSEC Cotonou le 10 août 2010). Rapport final, LSSEE/CRA-Agonkanmey/INRAB/Bénin; 2010; Ministère de L'agriculture de l'élevage et de la pèche, Cotonou, Benin.

Bargrizan, S., Smernik, R.J., Mosley, L.M., 2017. Development of a spectrophotometric method for determining pH of soil extracts and comparison with glass electrode measurements. Soil Sci. Soc. Am. J. 81, 1350–1358. https://doi.org/10.2136/sssaj2017.04.0119.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J., 2007. Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agric. Syst. 94, 13–25. https://doi.org/10.1016/j.agsy.2005.08.011.

Baudron, F., Tittonell, P., Corbeels, M., Letourmy, P., Giller, K.E., 2012. Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe. Field Crops Res. 132, 117–128. https://doi.org/10.1016/j.fcr.2011.09.008.
Bayu, T., 2020. Review on contribution of integrated soil fertility management for climate change mitigation and agricultural sustainability. Cogent Environ. Sci. 6. https://doi.org/10.1080/23311843.2020.1823631.
Berre, D., Adam, M., Koffi, C.K., Vigne, M., Gautier, D., 2022. Tailoring management practices to the structure of smallholder households in Sudano-Sahelian Burkina Faso: Evidence from current practices. Agric. Syst. 198. https://doi.org/10.1016/j.agsy.2022.103369.
Blanco-Canqui, H., Ruis, S.J., 2018. No-tillage and soil physical environment. Geoderma 326, 164–200. https://doi.org/10.1016/j.geoderma.2018.03.011.
Carter, S.E., Murwira, H.K., 1995. Spatial variability in soil fertility management and crop response in Mutoko Communal Area, Zimbabwe. Ambio 24, 77–84 jstor.org/stable/4314300.
Castellanos-Navarrete, A., Tittonell, P., Rufino, M.C., Giller, K.E., 2015. Feeding, crop residue and manure management for integrated soil fertility management–A case study from Kenya. Agric. Syst. 134, 24–35. https://doi.org/10.1016/j.agsy.2014.03.001.
Chikowo, R., Zingore, S., Snapp, S., Johnston, A., 2014. Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa. Nutr. Cycl. Agroecosystems 100, 1–18. https://doi.org/10.1007/s10705-014-9632-y.
Dabin, B., 1956. Contribution à l'étude de la fertilité des terres de barre, 11th ed. L'Agriculture Tropical.
Dabin, B., 1970a. Les facteurs chimiques de la fertilité des sols (Matière organique; phosphore).
Dabin, B., 1970b. Les facteurs chimiques de la fertilité des sols (bases échangeables, sels, utilisation des échelles de fertilité). Pédologie Dév. Paris ORSTOM 221–237.
Dassou, A.G., Yemadje, P.L., Atchadé, M.N., Gohouédé, L.C., Aboua, C.D., Boulakia, S., Balarabe, O., Sekloka, E., Tittonell, P., 2024. Conservation agriculture compared to conventional tillage improves the trade-off between ground-dwelling arthropod trophic groups for natural pest regulation in cotton cropping systems. Glob. Ecol. Conserv. 55. https://doi.org/10.1016/j.gecco.2024.e03223.
Descheemaeker, K., Ronner, E., Ollenburger, M., Franke, A.C., Klapwijk, C.J., Falconnier, G.N., Wichern, J., Giller, K.E., 2019. Which options fit best? Operationalizing the socio-ecological niche concept. Exp. Agric. 55, 169–190. https://doi.org/10.1017/S001447971600048X.
Diarisso, T., Corbeels, M., Andrieu, N., Djamen, P., Tittonell, P., 2015. Biomass transfers and nutrient budgets of the agro-pastoral systems in a village territory in south-western Burkina Faso. Nutr. Cycl. Agroecosystems 101, 295–315. https://doi.org/10.1007/s10705-015-9679-4.
Dignac, M.-F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., Freschet, G.T., Garnier, P., Guenet, B., Hedde, M., Klumpp, K., Lashermes, G., Maron, P.-A., Nunan, N., Roumet, C., Basile-Doelsch, I., 2017. Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. Agron. Sustain. Dev. 37, 14. https://doi.org/10.1007/s13593-017-0421-2.
Dimkpa, C., Adzawla, W., Pandey, R., Atakora, W.K., Kouame, A.K., Jemo, M., Bindraban, P.S., 2023. Fertilizers for food and nutrition security in sub-Saharan Africa: an overview of soil health implications. Front. Soil Sci. 3. https://doi.org/10.3389/fsoil.2023.1123931.
Diogo, R.V.C., Buerkert, A., Schlecht, E., 2010. Resource use efficiency in urban and peri-urban sheep, goat and cattle enterprises. Animal 4, 1725–1738. https://doi.org/10.1017/S1751731110000790.
Diogo, R.V.C., Dossou, J.A., Amadji, F., Bolo, P., Kihara, J.M., Gbedjissokpa, M.G., Hoek, R., van der, Kinyua, M., Mukiri, J., Sommer, R., 2021. Les engrais verts et les cultures de couverture au Bénin-informations tirées de la revue littéraire, de l'évaluation agronomique et de la modélisation de la durabilité des systèmes de culture. Rapp. CIAT 2021, 50.
Dossa, L.H., Abdulkadir, A., Amadou, H., Sangare, S., Schlecht, E., 2011. Exploring the diversity of urban and peri-urban agricultural systems in Sudano-Sahelian West Africa: an attempt towards a regional typology. Landsc. Urban Plan 102, 197–206. https://doi.org/10.1016/j.landurbplan.2011.04.005.
Dossouhoui, A., Yemadje, P.L., Diogo, R.V.C., Balarabe, O., Tittonell, P., 2023. Sedentarisation" of transhumant pastoralists results in privatization of resources and soil fertility decline in West Africa's cotton belt. Front. Sustain. Food Syst. 7. https://doi.org/10.3389/fsufs.2023.1120315.
DSA, 2024. Evolution de la production des cultures de 1996 à 2023 au Bénin [WWW Document]. URL ⟨https://dsa.agriculture.gouv.bj/statistics/vegetale⟩ (accessed 11.26.24).
FAO, 1984. Agro-ecological land Resources Assessment for agricultural Development Planning - A case Study of Kenya- Technical Annex 5 [WWW Document]. URL ⟨https://www.fao.org/4/t0828e/T0828E07.html⟩ (accessed 9.6.24).
Farahani, E., Emami, H., Forouhar, M., 2022. Effects of tillage systems on soil organic carbon and some soil physical properties. Land Degrad. Dev. 33, 1307–1320. https://doi.org/10.1002/ldr.4221.
Gnanglè, C.P., Kakaï, R.G., Assogbadjo, A.E., Vodounnon, S., Yabi, J.A., Sokpon, N., 2011. Tendances climatiques passées, modélisation, perceptions et adaptations locales au Bénin. Climatologie 8, 27–40. https://doi.org/10.4267/climatologie.259.
Government of Benin, 2021. ProSeR: Le Gouvernement œuvre pour la fin de la transhumance des ruminants [WWW Document]. Gouv. Répub. Bénin. URL ⟨https://www.gouv.bj/article/1663/⟩ (accessed 11.6.24).
Gram, G., Roobroeck, D., Pypers, P., Six, J., Merckx, R., Vanlauwe, B., 2020. Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: a meta-analysis. PloS One 15. https://doi.org/10.1371/journal.pone.0239552.
Guibert, H., 1999. Évolution de la matière organique et de la capacité d'échange cationique des alfisols tropicaux cultivés (phdthesis). Institut National Polytechnique de Lorraine.
Hammond, J., Rosenblum, N., Breseman, D., Gorman, L., Manners, R., van Wijk, M.T., Sibomana, M., Remans, R., Vanlauwe, B., Schut, M., 2020. Towards actionable farm typologies: scaling adoption of agricultural inputs in Rwanda. Agric. Syst. 183. https://doi.org/10.1016/j.agsy.2020.102857.
Hartemink, A., 2006. Assessing Soil Fertility Decline in the Tropics Using Soil Chemical Data. in: Advances in Agronomy. Academic Press, pp. 179–225. https://doi.org/10.1016/S0065-2113(05)89004-2.
Hauswirth, D., Pham, T.S., Wery, J., Tittonell, P., Jourdain, D., Affholder, F., 2015. Apports des typologies d'exploitations aux démarches de conception en agriculture de conservation: une étude de cas dans le nord du Vietnam. Cah. Agric. 24, 102–112. https://doi.org/10.1684/agr.2015.0744.
Hazelton, P., Murphy, B., 2016. Interpreting Soil Test Results, Third Edition. ed. Csiro Publishing, Melbourne.
Holden, S.T., 2018. Fertilizer and sustainable intensification in Sub-Saharan Africa. Glob. Food Secur 18, 20–26. https://doi.org/10.1016/j.gfs.2018.07.001.
Houessou, S.O., Dossa, L.H., Diogo, R.V., Houinato, M., Buerkert, A., Schlecht, E., 2019. Change and continuity in traditional cattle farming systems of West African Coast countries: a case study from Benin. Agric. Syst. 168, 112–122. https://doi.org/10.1016/j.agsy.2018.11.003.
Hougni, A., Sinha, M., Imorou, L., Aboua, C., Gotoechan Hodonou, H., Mensah G.A., 2016. Fiche technico-économique de OKP 768, variété éprouvée de cotonnier pour la région Centre. Dépôt légal N°9159 du 30/12/2016, Bibliothèque Nationale du Bénin (BnB), cr4ème trimestre – ISBN: 978-99919-2-716-9.
Hounkpatin, K.O., Bossa, A.Y., Yira, Y., Igue, M.A., Sinsin, B.A., 2022. Assessment of the soil fertility status in Benin (West Africa)–Digital soil mapping using machine learning. Geoderma Reg 28. https://doi.org/10.1016/j.geodrs.2021.e00444.
Huber, R., Bartkowski, B., Brown, C., El Benni, N., Feil, J.-H., Grohmann, P., Joormann, I., Leonhardt, H., Mitter, H., Müller, B., 2024. Farm typologies for understanding farm systems and improving agricultural policy. Agric. Syst. 213. https://doi.org/10.1016/j.agsy.2023.103800.
Igue, A.M., Saidou, A., Adjanohoun, A., Ezui, G., Attiogbe, P., Kpagbin, G., Gotoechan-Hodonou, H., Youl, S., Pare, T., Balogoun, I., 2013. Evaluation de la fertilité des sols au sud et centre du Bénin. Bull. Rech. Agron. Benin (BRAB) Numéro Spéc. Fertilité Maïs , 13–23. Available online: ⟨http://www.slire.net/download/1798/igue_et_al._evaluation_fertilit_.pdf⟩ (accessed on 9 October 2022).
INStaD, 2018. Statistiques Démographiques [WWW Document]. Inst. Natl. Stat. Démographie INStaD. URL https://instad.bj/statistiques/statistiques-demographiques#population (accessed 5.20.25).
Issahaku, G., Abdulai, A., 2020. Household welfare implications of sustainable land management practices among smallholder farmers in Ghana. Land Use Policy. p. 94. doi:10.1016/j.landusepol.2020.104502.
Jambo, I.J., Groot, J.C., Descheemaeker, K., Bekunda, M., Tittonell, P., 2019. Motivations for the use of sustainable intensification practices among smallholder farmers in Tanzania and Malawi. NJAS-Wagening. J. Life Sci. 89, 100306. https://doi.org/10.1016/j.njas.2019.100306.
Johnson, J.-M., Sila, A., Senthilkumar, K., Shepherd, K.D., Saito, K., 2021. Application of infrared spectroscopy for estimation of concentrations of macro-and micronutrients in rice in sub-Saharan Africa. Field Crops Res. 270. https://doi.org/10.1016/j.fcr.2021.108222.
Kassam, L., Farooq, M., Nawaz, A., Saharawat, Y.S., Reeves, T., Siddique, K., Pisante, M., Galieni, A., Basch, G., Friedrich, T., 2020. Advances in conservation agriculture volume 2: practice and benefits. Burleigh Dodds Science Publishing.
Kintché, K., Guibert, H., Sogbedji, J.M., Levêque, J., Tittonell, P., 2010. Carbon losses and primary productivity decline in savannah soils under cotton-cereal rotations in semiarid Togo. Plant Soil 336, 469–484. https://doi.org/10.1007/s11104-010-0500-5.
Kintché, K., Guibert, H., Sogbedji, J.M., Levêque, J., Bonfoh, B., Tittonell, P., 2015. Long-term mineral fertiliser use and maize residue incorporation do not compensate for carbon and nutrient losses from a Ferralsol under continuous maize–cotton cropping. Field Crops Res. 184, 192–200. https://doi.org/10.1016/j.fcr.2015.04.019.
Koné, I., Kouadio, K.-K.H., Kouadio, E.N., Agyare, W.A., Owusu-Prempeh, N., Amponsah, W., Gaiser, T., 2022. Assessment of soil fertility status in cotton-based cropping systems in Cote d'Ivoire. Front. Soil Sci. 2. https://doi.org/10.3389/fsoil.2022.959325.
Kuivanen, K.S., Alvarez, S., Michalscheck, M., Adjei-Nsiah, S., Descheemaeker, K., Mellon-Bedi, S., Groot, J.C.J., 2016. Characterising the diversity of smallholder farming systems and their constraints and opportunities for innovation: a case study from the Northern Region, Ghana. NJAS Wagening. J. Life Sci. 78, 153–166. https://doi.org/10.1016/j.njas.2016.04.003.
Lal, R., 2021. Soil organic matter and feeding the future: environmental and agronomic impacts, 1st ed, Advances in soil science. CRC Press, Boca Raton. https://doi.org/10.1201/9781003102762.
Landon, J.R., 2013. Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. Routledge, London. https://doi.org/10.4324/9781315846842.
Laub, M., Corbeels, M., Ndungu, S.M., Mucheru-Muna, M.W., Mugendi, D., Necpalova, M., Van de Broek, M., Waswa, W., Vanlauwe, B., Six, J., 2023. Combining manure with mineral N fertilizer maintains maize yields: evidence from four long-term experiments in Kenya. Field Crops Res 291, 108788. https://doi.org/10.1016/j.fcr.2022.108788.

Li, G., Yu, C., Shen, P., Hou, Y., Ren, Z., Li, N., Liao, Y., Li, T., Wen, X., 2024. Crop diversification promotes soil aggregation and carbon accumulation in global agroecosystems: a meta-analysis. J. Environ. Manag. 350. https://doi.org/10.1016/j.jenvman.2023.119661.

Maboudou Alidou, G., Niehof, A., 2020. Responses of rural households to the cotton crisis in Benin. Sustainability 12, 4207. https://doi.org/10.3390/su12104207.

MAEP, 2021. Sous-secteur de l'élevage: Le Gouvernement lance le Projet de sédentarisation des troupeaux de ruminants au Bénin (ProSeR) [WWW Document]. Gouv. Répub. Bénin. URL ⟨https://www.gouv.bj/article/1624/sous-secteur-elevage-gouvernement-lance-projet-sedentarisation-troupeaux-ruminants-benin-proser-/⟩ (accessed 9.6.24).

Mallarino, A., Sawyer, J., Barnhart, S., 2013. A general guide for crop nutrient and limestone recommendations in Iowa. Department of Agronomy, Iowa State University, Iowa (2013).

Mehlich, A., 1953. Determination of P, Ca, mg, K, Na, and NH4. N. C. Soil Test Div. Mimeo 1953 2, 23–89. North Carolina Soil Test Div., Raleigh, NC (1953).

Miller, W.P., Miller, D.M., 1987. A micro-pipette method for soil mechanical analysis. Commun. Soil Sci. Plant Anal. 18, 1–15. https://doi.org/10.1080/00103628709367799.

Musumba, M., Palm, C.A., Komarek, A.M., Mutuo, P.K., Kaya, B., 2022. Household livelihood diversification in rural Africa. Agric. Econ. 53, 246–256. https://doi.org/10.1111/agec.12694.

Ndambi, O.A., Pelster, D.E., Owino, J.O., de Buisonjé, F., Vellinga, T., 2019. Manure Management practices and policies in Sub-Saharan Africa: implications on manure quality as a fertilizer. Front. Sustain. Food Syst. 3. https://doi.org/10.3389/fsufs.2019.00029.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. Methods. Soil Anal. Part 3 Chem. Methods 5, pp. 961–1010. https://doi.org/10.2136/sssabookser5.3.c34.

Nezomba, H., Mtambanengwe, F., Tittonell, P., Mapfumo, P., 2017. Practical assessment of soil degradation on smallholder farmers' fields in Zimbabwe: integrating local knowledge and scientific diagnostic indicators. Catena 156, 216–227. https://doi.org/10.1016/j.catena.2017.04.014.

Ngaiwi, M.E., Molua, E.L., Sonwa, D.J., Meliko, M.O., Bomdzele, E.J., Ayuk, J.E., Castro-Nunez, A., Latala, M.M., 2023. Do farmers' socioeconomic status determine the adoption of conservation agriculture? An empirical evidence from Eastern and Southern Regions of Cameroon. Sci. Afr. 19, e01498. https://doi.org/10.1016/j.sciaf.2022.e01498.

Nguemezi, C., Tematio, P., Yemefack, M., Tsozue, D., Silatsa, T.B.F., 2020. Soil quality and soil fertility status in major soil groups at the Tombel area, South-West Cameroon. Heliyon 6, e03432. https://doi.org/10.1016/j.heliyon.2020.e03432.

Ntamwira, J., Ocimati, W., Blomme, G., Lubobo, A.K., Mwarabu Lolonga Pyame, D., Dhed'a Djailo, B., 2023. Innovative agroecological practices can restore degraded farmlands and revive crop yields. Front. Sustain. Food Syst. 7. https://doi.org/10.3389/fsufs.2023.1017341.

OECD, 1982. The OECD List of Social Indicators, Paris - Google Scholar [Document]. URL ⟨https://scholar.google.com/scholar_lookup?title=The%20OECD%20List%20of%20Social%20Indicators&author=OECD&publication_year= 1982⟩ (accessed 5.17.24).

Ollabodé, N., Obe, M.M., Kpadé, C.P., Sekloka, E., 2024. Typologie et performances économiques des exploitations cotonnières au Bénin. Économie Rural. Agric. Aliment. Territ 49–67. https://doi.org/10.4000/economierurale.12345.

Olounlade, O.A., Li, G.-C., Kokoye, S.E.H., Dossouhoui, F.V., Akpa, K.A.A., Anshiso, D., Biaou, G., 2020. Impact of participation in contract farming on smallholder farmers' income and food security in rural Benin: PSM and LATE parameter combined. Sustainability 12, 901. https://doi.org/10.3390/su12030901.

Olsen,S.R.1954 Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. U.S. Department of Agriculture. Washington, D.C.

Omotoso, A.B., Letsoalo, S., Olagunju, K.O., Tshwene, C.S., Omotayo, A.O., 2023. Climate change and variability in sub-Saharan Africa: A systematic review of trends and impacts on agriculture. J. Clean. Prod. 414. https://doi.org/10.1016/j.jclepro.2023.137487.

Orzechowski, M., Smó, S., Dlugosz, J., Pozniak, P., 2014. Measurements of texture of soils formed from glaciolimnic sediments by areometric method, pipette method and laser diffraction method. Soil Sci. Annu 65, 72. https://doi.org/10.2478/ssa-2014-0011.

Oyetunde-Usman, Z., Olagunju, K.O., Ogunpaimo, O.R., 2021. Determinants of adoption of multiple sustainable agricultural practices among smallholder farmers in Nigeria. Int. Soil Water Conserv. Res. 9, 241–248. https://doi.org/10.1016/j.iswcr.2020.10.007.

Paracchini, M.L., Justes, E., Wezel, A., Zingari, P.C., Kahane, R., Madsen, S., Scopel, E., Hérault, A., Bhérer-Breton, P., Buckley, R., 2020. Agroecological practices supporting food production and reducing food insecurity in developing countries. A Study Sci. Lit. 17 Ctries. https://doi.org/10.2760/82475.

Pieri, C., Moreau, R., 1987. Fertilité des sols et fertilisation des cultures tropicales. L'expérience du CIRAD et de l'ORSTOM. Presented at the Seminar on french agronomie research in the intertropical zone, ORSTOM, Washington.

Queisser, M., Ladaique, M., D'Ercole, M.M., 2022. OECD List of Social Indicators. In: Maggino, F. (Ed.), Encyclopedia of Quality of Life and Well-Being Research. Springer International Publishing, Cham, pp. 1–3. https://doi.org/10.1007/978-3-319-69909-7_2001-2.

Rayne, N., Aula, L., 2020. Livestock manure and the impacts on soil health: a review. Soil Syst. 4, 64. https://doi.org/10.3390/soilsystems4040064.

Ripoche, A., Crétenet, M., Corbeels, M., Affholder, F., Naudin, K., Sissoko, F., Douzet, J.-M., Tittonell, P., 2015. Cotton as an entry point for soil fertility maintenance and food crop productivity in savannah agroecosystems–Evidence from a long-term experiment in southern Mali. Field Crops Res 177, 37–48. https://doi.org/10.1016/j.fcr.2015.02.013.

Rowland, A.P., Haygarth, P.M., 1997. Determination of total dissolved phosphorus in soil solutions. J. Environ. Qual. 26, 410–415. https://doi.org/10.2134/jeq1997.00472425002600020011x.

Rufino, M.C., Tittonell, P., Van Wijk, M.T., Castellanos-Navarrete, A., Delve, R.J., De Ridder, N., Giller, K.E., 2007. Manure as a key resource within smallholder farming systems: analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livest. Sci. 112, 273–287. https://doi.org/10.1016/j.livsci.2007.09.011.

Samaké, O., Smaling, E.M.A., Kropff, M.J., Stomph, T.J., Kodio, A., 2005. Effects of cultivation practices on spatial variation of soil fertility and millet yields in the Sahel of Mali. Agric. Ecosyst. Environ. 109, 335–345. https://doi.org/10.1016/j.agee.2005.02.024.

Samson, M.-E., Chantigny, M.H., Vanasse, A., Menasseri-Aubry, S., Royer, I., Angers, D. A., 2020. Management practices differently affect particulate and mineral-associated organic matter and their precursors in arable soils. Soil Biol. Biochem. 148. https://doi.org/10.1016/j.soilbio.2020.107867.

Schofield, R.K., Taylor, A.W., 1955. The measurement of soil pH. Soil Sci. Soc. Am. J. 19, 164–167. https://doi.org/10.2136/sssaj1955.03615995001900020013x.

Sekaran, U., Lai, L., Ussiri, D.A.N., Kumar, S., Clay, S., 2021. Role of integrated crop-livestock systems in improving agriculture production and addressing food security – A review. J. Agric. Food Res. 5. https://doi.org/10.1016/j.jafr.2021.100190.

Šimon, T., Javůrek, M., Mikanová, O., Vach, M., 2009. The influence of tillage systems on soil organic matter and soil hydrophobicity. Soil Tillage Res. 105, 44–48. https://doi.org/10.1016/j.still.2009.05.004.

Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241, 155–176. https://doi.org/10.1023/A:1016125726789.

Sui, Y., Gao, Q., 2023. Farmers' endowments, technology perception and green production technology adoption behavior. Sustainability 15. https://doi.org/10.3390/su15097385.

Suri, T., Udry, C., 2022. Agricultural technology in Africa. J. Econ. Perspect. 36, 33–56. https://doi.org/10.1257/jep.36.1.33.

Tittonell, P., Gérard, B., Erenstein, O., 2015. Tradeoffs around crop residue biomass in smallholder crop-livestock systems–What's next? Agric. Syst. 134, 119–128. https://doi.org/10.1016/j.agsy.2015.02.003.

Tittonell, P., Muriuki, A., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., Vanlauwe, B., 2010. The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa – A typology of smallholder farms. Agric. Syst. 103, 83–97. https://doi.org/10.1016/j.agsy.2009.10.001.

Tittonell, P., Shepherd, K.D., Vanlauwe, B., Giller, K.E., 2008. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya—An application of classification and regression tree analysis. Agric. Ecosyst. Environ. 123, 137–150. https://doi.org/10.1016/j.agee.2007.05.005.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. Agric. Ecosyst. Environ. 110, 149–165. https://doi.org/10.1016/j.agee.2005.04.001.

Tovihoudji, P.G., Akpo, F.I., Tassou Zakari, F., Ollabodé, N., Yegbemey, R.N., Yabi, J.A., 2023. Diversity of soil fertility management options in maize-based farming systems in northern Benin: a quantitative survey. Front. Environ. Sci. 11. https://doi.org/10.3389/fenvs.2023.1089883.

Tovihoudji, P.G., Sossa, E.L., Egah, J., Agbangba, E.C., Akponikpè, P.B.I., Yabi, J.A., 2024. Resource endowment and sustainable soil fertility management strategies in maize farming systems in northern Benin. Front. Sustain. Resour. Manag 3. https://doi.org/10.3389/fsrma.2024.1354981.

Tully, K., Sullivan, C., Weil, R., Sanchez, P., 2015. The state of soil degradation in sub-saharan africa: baselines, trajectories, and solutions. Sustainability 7, 6523–6552. https://doi.org/10.3390/su7066523.

Valbuena, D., Groot, J.C.J., Mukalama, J., Gérard, B., Tittonell, P., 2015. Improving rural livelihoods as a "moving target": trajectories of change in smallholder farming systems of Western Kenya. Reg. Environ. Change 15, 1395–1407. https://doi.org/10.1007/s10113-014-0702-0.

Vall, E., Orounladji, B.M., Berre, D., Assouma, M.H., Dabiré, D., Sanogo, S., Sib, O., 2023. Crop-livestock synergies and by-products recycling: major factors for agroecology in West African agro-sylvo-pastoral systems. Agron. Sustain. Dev. 43, 70. https://doi.org/10.1007/s13593-023-00908-6.

Wanjiku Kamau, J., Biber-Freudenberger, L., Lamers, J.P.A., Stellmacher, T., Borgemeister, C., 2019. Soil fertility and biodiversity on organic and conventional smallholder farms in Kenya. Appl. Soil Ecol. 134, 85–97. https://doi.org/10.1016/j.apsoil.2018.10.020.

Wezel, A., Casagrande, M., Celette, F., Vian, J.-F., Ferrer, A., Peigné, J., 2014. Agroecological practices for sustainable agriculture. A review. Agron. Sustain. Dev. 34, 1–20. https://doi.org/10.1007/s13593-013-0180-7.

Willy, D.K., Muyanga, M., Mbuvi, J., Jayne, T., 2019. The effect of land use change on soil fertility parameters in densely populated areas of Kenya. Geoderma 343, 254–262. https://doi.org/10.1016/j.geoderma.2019.02.033.

Yegbemey, R.N., 2021. Farm-level land use responses to climate change among smallholder farmers in northern Benin, West Africa. Clim. Dev. 13, 593–602. https://doi.org/10.1080/17565529.2020.1844129.

Yemadje, R.H., Crane, T.A., Mongbo, R.L., Saïdou, A., Azontonde, H.A., Kossou, D.K., Kuyper, T.W., 2014. Revisiting land reform: land rights, access, and soil fertility management on the Adja Plateau in Benin. Int. J. Agric. Sustain 12, 355–369. https://doi.org/10.1080/14735903.2014.909645.

Yemadje, P.L., Takpa, O., Amonmide, I., Balarabe, O., Sekloka, E., Guibert, H., Tittonell, P., 2022. Limited yield penalties in an early transition to conservation agriculture in cotton-based cropping systems of Benin. Front. Sustain. Food Syst. 6. https://doi.org/10.3389/fsufs.2022.1041399.

Yemadje, P.L., Tovihoudji, P.G., Koussihouede, H., Imorou, L., Balarabe, O., Boulakia, S., Sekloka, E., Tittonell, P., 2025. Reducing initial cotton yield penalties in a transition to conservation agriculture through legume cover crop cultivation–evidence from Northern Benin. Soil Tillage Res 245. https://doi.org/10.1016/j.still.2024.106319.

Zingore, S., Murwira, H.K., Delve, R.J., Giller, K.E., 2007. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agric. Ecosyst. Environ. 119, 112–126. https://doi.org/10.1016/j.agee.2006.06.019.

Zingore, S., Tittonell, P., Corbeels, M., van Wijk, M.T., Giller, K.E., 2011. Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. Nutr. Cycl. Agroecosystems 90, 87–103. https://doi.org/10.1007/s10705-010-9414-0.

Zohoungbogbo, H.P.F., Montin, A., Lègba, E.C., Houdégbé, C.A., Fassinou Hotègni, N.V., Achigan-Dako, E.G., 2018. Fiche technique synthétique pour la production du maïs jaune (Zea mays L.). Bibliothèque Nationale du Bénin, 3ième trimestre Septembre, 2018, ISBN978-99919-78-48-2, Dépôt légal N° 10668 du 06/09/18.