



Crop-livestock synergies and by-products recycling: major factors for agroecology in West African agro-sylvo-pastoral systems

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Abstract

In Western Africa, agro-sylvo-pastoral systems are dominant and food demand is booming. To meet this demand, many farmers intensify the production with industrial inputs (mineral fertilizers, feeds, pesticides, herbicides). However, the price of these inputs is rocketing. To face this issue, some farmers reconsider crops, livestock, and tree synergies and by-product recycling to increase their production sustainably at a lower cost. The study aimed to characterize the diversity of Koumbia's farming systems and to assess farming systems' technical performance in an agroecological perspective. We surveyed 391 farms in the county of Koumbia (Burkina Faso). Considering 15 agricultural practices (4 on by-products recycling, 4 on soil protection, 4 on industrial inputs limitation, 2 on smart use of natural resources, and 1 on cropping diversification), a multivariate analysis (PCA+HAC) combined to an agroecology (Ae) scoring system (−15 to +15) based on 15 specific indicators (one/practice), we highlighted 3 agroecological farming systems clusters. These clusters are distributed along a gradient of agroecology intensity (Ae+: high degree of Ae, Ae+/-: medium degree, and Ae−: poor degree). Ae+ farms (Ae score: +3.0) group 17% of the farms, Ae+/- (Ae score: −4.5) group 58% of the farms, and Ae− (Ae score: −10.5) group 25% of the farms. Ae+ raise more livestock and recycle a higher rate of crop-livestock by-products in fodder, organic manure, and mulch. These recycling practices are facilitated by better levels of equipment for transportation and storage and soil water and crop residue conservation measures, including maintenance of the wooded park on the cultivated fields. This set of practices, which close better the agricultural system, produces a systemic effect which has a positive impact on yields and on the whole ecosystem. Our findings outline for the first time that crop-livestock synergies and by-product recycling are major factors of agroecological transition in agro-sylvo-pastoral systems.

Keywords Crop-livestock systems · Fodder storage and conservation · Organic manure · Nutrients and biomasses recycling · Input reduction · Agroecosystem biodiversity · Agroecosystem synergies

1 Introduction

African farmers face multiple challenges. There is widespread recognition of the need for alternatives to current African agricultural and food systems to ensure they provide diverse and healthy food, support rural livelihoods, and do not degrade even more the environment (HLPE 2019). Agroecology transition in Africa has been suggested as contributing to solutions to these challenges (Viability Project Team 2023). Agroecology (Ae) is a body of knowledge, practices, and political movements that aim to support the transformation of food and agricultural systems to long-term social and environmental sustainability (Wezel et al. 2009). Agroecology is grounded in principles that are adapted and implemented in various ways depending on the local context (Wezel et al.

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2020). In agro-sylvo-pastoral systems of Western Africa, crop-livestock by-product recycling, crop-livestock-tree synergies, soil protection, smart use of natural resources, and biodiversification of farming systems are emerging as crucial components for agroecological transition.

In the savannah areas of West Africa, agro-sylvo-pastoral systems are overwhelmingly dominant and involve millions of farming households (Séré and Steinfeld 1996; Robinson et al. 2011).

In these farming systems, synergies between crops, trees, and animals take on many different forms and vary in intensity across farms (Powell et al. 2004; Hendrickson et al. 2008; Vall et al. 2017). These synergies form the basis and hallmark of these systems' agroecological practices (Debray et al. 2019; Vall et al. 2019).

These synergies are longstanding (Landais and Lhoste 1990; Dugué et al. 2004; Powell et al. 2004; Hendrickson et al. 2008). However, given today's unprecedented rise in human pressure on land, as well as the spread of more intensive farming techniques via cotton (row crops, use of herbicides and pesticides, mechanized and increasingly motorized farming), and the effects of climate change, they are taking on new forms (Vall et al. 2019).

In the past, these synergies were based upon low labor-intensive practices (land left fallow, grazing of crop residues, manure deposit on cropland by livestock night corralling), all of which were viable in a context of low pressure on resources (Landais and Lhoste 1990; Milleville and Serpantié 1994). Today, due to increasing competition for spaces and natural resources, they are now being replaced by practices that involve more work, more control, and more investment. Here are some examples of these emerging agricultural practices: soil and water conservation measures in the fields; selectively managing tree species; diversifying

farm machinery; monitoring the herd movements on pasture; improving animal housing; increasing fodder residue storage; developing fodder crops; diversifying animal feed rations; diversifying manure production methods in pens, pits, and biodigesters; managing plant cover on crop plots (Vall et al. 2019; Fig. 1). According to some researchers, they often play a significant role in the sustainability of farming systems (Rudel et al. 2016).

Our assumption is that today, agroecology at the farm system level in West African agro-sylvo-pastoral systems is mainly based on new livestock feeding management practices, integrating pasture grazing and stall housing, and on a growing number of crop-livestock by-product recycling processes introduced by farmers.

In this paper, we highlight for the first time that crop-livestock synergies and by-product recycling are major factors for agroecology in West African agro-sylvo-pastoral systems through quantitative metrics. These findings are based on a survey of 391 agro-sylvo-pastoral farms located in western Burkina Faso around Koumbia, in the heart of the country's cotton-producing area.

This paper has two main objectives:

- Characterizing the diversity of Koumbia's farming systems considering 15 agricultural practices related to agroecological principles (4 on recycling of crops and livestock by-products, 4 on soil protection, 4 on limitation of industrial inputs, 2 on smart use of natural resources, and 1 on cropping systems biodiversification). The 15 agricultural practices were combined to an Ae scoring system based on 15 specific indicators (one/practice; Ae scoring between -15 and +15) in order to identify Ae farming systems clusters;

Fig. 1 Fodder storage and accumulation of organic manure under a herd of cattle kept at home.



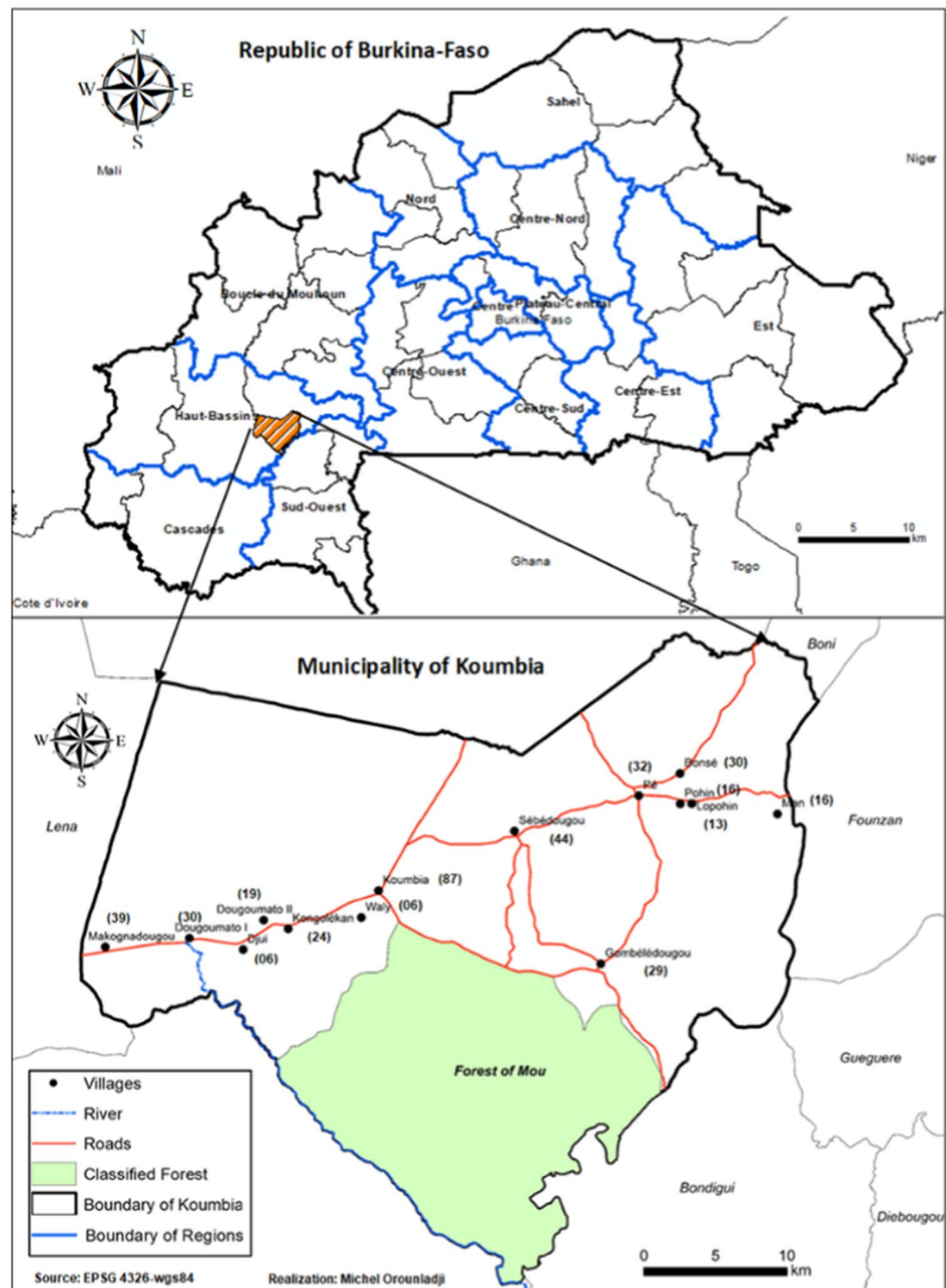
- In depth analysis between the Ae farming systems clusters: (1) structural characteristics of each Ae farming system cluster; (2) assessing the Ae cluster farming systems' technical performance; (3) interpret the technical performance of Ae clusters by representing their agroecological systemic functioning (recycling of crops and livestock by-products, soil protection, spontaneous use of resources, cropping systems bio-diversification and on limitation of industrial inputs) and taking into account their structural characteristics.

2 Materials and methods

2.1 Study site description

The municipality of Koumbia was chosen because it has been documented as a representative area of West African agrosylvo-pastoral territories (Vall et al. 2006, 2019). Located in the western part of Burkina Faso, in the Tuy province and in the heart of the country's cotton-producing area, it comprises 14 villages and several farming hamlets (Fig. 2).

Fig. 2 Map of the municipality of Koumbia and the farms surveyed during the study.



It covers an area of 1358 km², 30% of which is made up of protected forests. According to the last census, the population is estimated at 46,005 (INSD 2022). The indigenous people belong to the Bwaba ethnic group. Since the 1980s, the municipality has absorbed a large influx of people from the north of the country (Mossi, Fulani herders, etc.) in search of land, pasture, and more favorable weather conditions. The two main economic activities of the population are agriculture and livestock farming. The farming system is rainfed with intermixed/scattered tree cover (*Vitellaria paradoxa*, *Parkia biglobosa*, *Faidherbia albida*), powered by animal traction (with a trend towards motorization), relatively input-intensive for cotton, maize, and rice, and with a low level of inputs for other crops (sorghum, millet, groundnut, cowpea). Cattle, sheep, and goat breeding is based on optimizing the use of spontaneous vegetation on pasture, crop residues, and a few agro-industrial by-products. Storing crop by-products as dry season forage and producing organic manure is becoming increasingly common. In three decades, the population has tripled, resulting in an increase in land being cleared and the end of fallowing, leading to a higher risk of declining soil fertility. As a result of crop expansion, herders are faced with the shrinking of their traditional pastoral areas. The dramatic growth in population density (+380% between 1985 and 2020, during which it rose from 10 to 48 inhabitants/km² in the legally usable area, i.e., excluding protected forests) has led to fierce competition for agro-sylvo-pastoral resources. It has also increasingly encouraged farmers to recycle agricultural and livestock by-products or to practice transhumance with all or part of their livestock.

2.2 Sample of Koumbia farms studied

The survey was conducted among 391 farms in the 14 villages of the municipality of Koumbia, with about 4000 farms, i.e., a sampling rate of around 10%. To consider the diversity and weight of the main types of farms, the sample was reasoned by considering the proportion of the 3 main local types of farms (crop-oriented farms ~ 60%; livestock-oriented farms ~ 20%; and crop-livestock-oriented farms ~ 20%), as well as the area cultivated by the farm (in ha) and the livestock owned by the farm (in TLU knowing that 1 TLU = 1 bovine of 250 kg) as proposed by Vall et al. (2017) in previous studies. Following these criteria, the sample of 391 farms studied is distributed as follows:

- 225 crop-oriented farms (58% of farms in the sample)
 - 70 very small crop-oriented farms (< 5 ha, < 10 TLU)
 - 101, medium size crop-oriented farms (5-10 ha, < 10 TLU)
- 54 large crop-oriented farms (> 10 ha; < 10 TLU)
- 78 crop-livestock farms (20 % of farms in the sample; > 10 ha, > 10 TLU)
- 88 livestock-oriented farms (22 % of farms in the sample)
 - 41 small livestock-oriented farms (< 7.5 ha; 10 -29 TLU)
 - 47 large livestock-oriented farms (< 7.5 ha; > 20 TLU)

2.3 Data acquisition

Data was collected in a single-pass survey through a digital questionnaire hosted on the KoboToolBox platform and deployed on the KoBoCollect v2021.3.4 application.

Enumerators surveyed farm managers between September and October 2021. The reference period for the survey was a full year running from May 2020 to May 2021. A guide was produced to help enumerators fully understand the questions and find the information needed to phrase the answers correctly.

On the day of the survey, once the respondents' consent to the results being published had been secured, the enumerators started collecting data on the general characteristics of the farms (farm manager's ID and contact details, information about dependants and staff, equipment, tools, and buildings for farming and livestock), followed by detailed data on the following:

- Fields (acreage, facilities, tree density);
- Crops (plot size, production, soil preparation, use of organic manure and mineral fertilizers, use of herbicides, soil coverage with crop residues or mulch in the dry season);
- Storage of agricultural by-products (quantities and storage methods for straw, tops, stalks);
- Livestock management in draft cattle, dairy cows, suckling cattle, and sheep and goat production units (number of heads/farm, grazing/zero grazing livestock, fodder distribution and feed supplementation, milk production per cow, births, sales, deaths);
- Production and use of organic manure (in pits, pens, biogas digesters, or deposit in fields during livestock night corralling).

2.4 Rationale for the agroecological practices considered

In order to study the agroecological nature of the farming systems, we focused on the principles of agroecology suggested by Wezel et al. (2020) that are more specific to this level of analysis, namely, synergies, recycling, input reduction,

bio-diversification of the cropping system with pulses, soil health, and animal welfare. As a result, we identified 15 agricultural practices implementing these agroecological principles, for which there is still significant room for improvement in the short term, without major structural changes at the farm level to improve the level of agroecology of the farming system:

- The recycling of crops and livestock by-products (dung, cotton stalks, cereal straw, legume tops) to produce fodder, organic manure, and mulch;
- Soil protection (ground coverage or mulch, stone barriers, grass strips, minimum tillage);
- The use of spontaneous vegetation (pastures, wooded areas);
- The limited uses of industrial inputs (mineral fertilizers, herbicides, animal feed) and agricultural equipment powered by internal combustion engines;
- Cropping system bio-diversification (legumes cultivation)

Figure 3 provides the list of all 15 selected practices and a diagram showing the sequence of practices over the course of a year in relation to the main stages in the agricultural calendar.

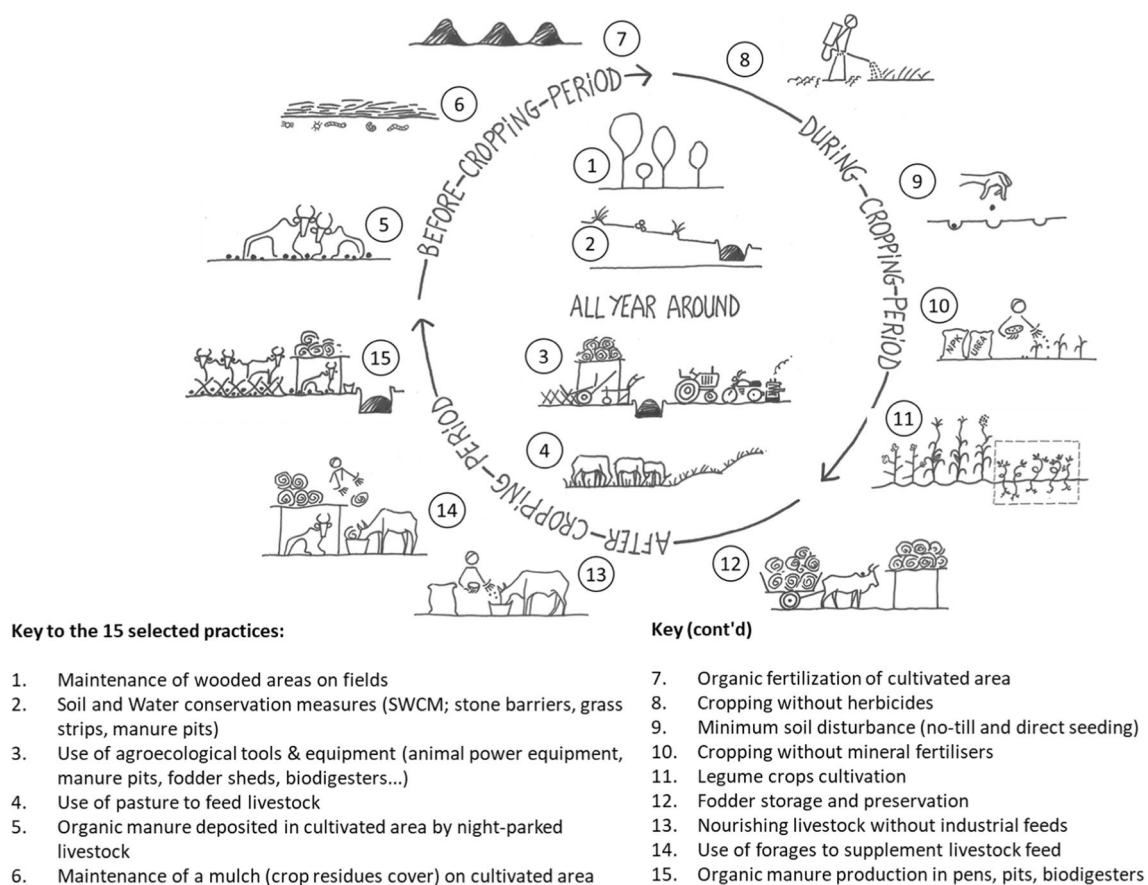


Fig. 3 Schematic diagram of the agro-sylvo-pastoral system and the 15 agricultural practices selected to assess the agroecological nature of the study area's production systems.

2.5 Data analysis

Each practice has been characterized by a quantitative indicator as shown in Table 1 Description of the 15 agricultural practices, indicators, and indicator calculation principles used in this study to score the level of agroecology.

2.5.1 From data to farm groups

The complete dataset includes 391 individuals and 36 variables (15 indicators for agricultural practices, 8 variables of farm structures, and 13 performance variables). In order to develop the typology of farming systems considering the 15 agricultural practices considered, a first category of farms with no livestock (zero tropical livestock unit (TLU)) was created. A multivariate analysis based on principal component analysis (PCA) and hierarchical ascending classification (HAC) was then used to classify the other farms with TLUs.

The 25 farms with no livestock (zero TLU) were treated as a separate group. These farms are geared towards small or very small-scale agriculture (according Vall et al. 2017 criteria and typology). Since PCA analysis does not tolerate

Table 1 Description of the 15 agricultural practices, indicators, and indicator calculation principles used in this study to score the level of agroecology. Key: *TLU*, tropical livestock unit (1 TLU = head of cattle with a live weight of 250 kg); *OM*, organic manure; *FCFA*, Franc CFA; *SWCM*, soil and water conservation measures.

No.	Agricultural practices	Indicators of the agricultural practice	Indicator calculation principles
1	Maintenance of wooded areas on fields	Number of trees/ha	$\sum_{\text{Fields}} [\text{Field (ha)} \times \text{Field tree density (tree/ha)}] / \text{Total area of farm's field (ha)}$; field tree density estimated with a 6 stages scoring scale from 0 to 25 trees/ha
2	Soil and Water conservation measures (stone barriers, grass strips, manure pits)	Farm land under SWCM practices (%)	$\sum_{\text{Fields}} [\text{Field with SWCM practices (ha)}] / \text{Total area of farm's fields (ha)}$
3	Use of agroecological tools and equipment (draft animal power tools and animals, manure pits, fodder sheds, biogas digesters)	Proportion of agroecological tools and equipment (%)	$\sum_{\text{Tools and Equipment}} [\text{Value of agroecological tools and equipment (FCFA)}] / \text{Total value of farm tools and equipment (FCFA)}$
4	Use of pasture to feed livestock	Farm's grazing livestock (%)	Grazing livestock (TLU) / Total farm's Livestock (TLU)
5	Organic manure deposited in cultivated area by night-parked livestock	OM deposited by night parked livestock (kgDM) / cultivated area (ha)	$\sum_{\text{park-livestock units}} [\text{TLU of night-parked livestock} \times \text{Number of night} \times 1,4 \text{ kgMS} \cdot \text{night}^{-1}] / \text{Total cultivated area (ha)}$
6	Maintenance of a mulch (crop residues cover) on cultivated area at the end of the dry season	Mulch density (kgDM/ ha)	$\sum_{\text{cultivated plots}} [\text{Plot area (ha)} \times \text{Mulch density (kgMS/ha)}] / \text{Total cultivated area (ha)}$; Mulch density estimated with a 6 stages scoring scale from 0 to 6 tMS/ha for maize, rice, and pearl millet straws, 0 to 7 tMS/ha for sorghum straws, 0 to 2 tMS/ha for cotton stalks—pulses: not considered
7	Organic fertilization of cultivated area	Cultivated area fertilized with organic manure (%)	$\sum_{\text{cultivated plots}} [\text{Plot that has received OM (ha)}] / \text{Total cultivated area (ha)}$
8	Cropping without herbicides	Cultivated area without any herbicides (%)	Cultivated area without herbicides (ha) / Total cultivated area (ha)
9	Minimum soil disturbance	Cultivated area under no-till and direct seeding (%)	Cultivated area under no-till and direct seeding (ha) / Total cultivated area (ha)
10	Cropping without mineral fertilizers	Cultivated area without any mineral fertilizers (%)	Cultivated area without mineral fertilizers (ha) / Total cultivated area (ha)
11	Legume crops cultivation	Cultivated area under legume crops (%)	Cultivated area under legume crops (ha) / Total cultivated area (ha)
12	Fodder storage and preservation	Stored fodder (kg) / Cereals and legumes cultivated area (ha)	Quantity of stored plant residues for livestock feeding on the farm (kgMS) / Total cereals and legumes cultivated area (ha)
13	Nourishing livestock without industrial feeds	Farm's livestock nourished without feed at all (%)	Farm's livestock nourished without feeds (TLU) / Total farm's livestock (TLU)
14	Use of forages to supplement livestock feed (crops residues + cultivated forages)	Farm's livestock receiving forages (%)	Farm's livestock receiving forages (TLU) / Total farm's livestock (TLU)
15	Organic manure production in pens, pits, biogas digesters for cultivated area	OM produced (kgDM) / cultivated area (ha)	$[\text{OM}_{\text{produced in pens}} + \text{OM}_{\text{produced in pits}} + \text{OM}_{\text{produced in biogas digesters}} (\text{kgDM})] / \text{Total cultivated area (ha)}$

missing data, indicators 4, 13, and 14 in Table 1 (% of TLUs grazing, % of TLUs receiving feed, % of TLUs receiving fodder) could not be measured as the total number of TLUs was in the denominator to calculate these ratios. This is why we classified them separately.

A PCA followed by an HAC was carried out based on the remaining 366 farms considering the 15 agricultural practices. The PCA and HAC enabled to define 6 groups of farming systems considering these agricultural practices.

Subsequently, the 391 (366 + 25) farms were split into 7 (1 + 6) groups of farming systems considering the 15 agricultural practices. We performed variance analyses (ANOVA) using XLSTAT (XLSTAT, version 2019.4.1.63353) to examine the significance of differences among the seven groups in relation to the 15 agricultural practices of the PCA. Whenever a significant difference was found ($p < 0.05$), it was followed by a Newman Keuls test.

2.5.2 From farm groups to agroecological farming system clusters

To establish an agroecological (Ae) clustering of farms groups, we used the following Ae scoring system:

- 1) For a given indicator (i : 1 to 15) for a given farm group (G1 to G7), its value ($Indic_i^G$) was compared to the average of the indicator i of the 7 farm groups (\overline{Indic}_i)
- 2) The value 1 or 0.5 or -1 has been assigned to “ i ” depending on the position of $Indic_i^G$ with respect to \overline{Indic}_i :
 - 1 if $Indic_i^G > 1.05 \times \overline{Indic}_i$
 - 0.5 if $Indic_i^G < 1.05 \times \overline{Indic}_i$
 - -0.5 if $0.95 \times \overline{Indic}_i < Indic_i^G < \overline{Indic}_i$
 - -1 if $Indic_i^G < 0.95 \times \overline{Indic}_i$

In this way, it can be defined for a farm group whether an indicator value is significantly above or below a median zone (between 0.95 and 1.05 around the mean).

- 3) Scoring Ae: For a given farm group (Gx), the sum of the 15 indicators converted into a score (1; 0.5; -0.5 ; -1) establishes a score between -15 and $+15$ which we interpret as a score of agroecology in the sense that it reflects the effort deployed to implement the 15 practices. The closer the score is to 15, the more the farm is agroecological, and the closer the score is to -15 , the less it is. This Ae score has a local value and does not claim to qualify in absolute terms the Ae character of an agricultural system.
- 4) Ae clustering: The groups (G1 to G7) were then grouped into Ae clusters based on the proximity of their Ae scoring (Ae+; Ae+/-; and Ae-).

2.5.3 In-depth analysis of the Ae farming system clusters

We characterized the structural features of each agroecological farming system cluster using eight structure variables (cultivated area in ha, livestock in TLU, number of family members, number of family assets, number of employees, assets/ha, total value of agricultural equipment in FCFA, value of agroecological equipment in FCFA).

We assessed the technical performances of each agroecological farming system clusters using thirteen technical performance variables: yields for each of the 12 crops (in kg/ha: cotton, maize, red sorghum, white sorghum, millet, rice, groundnut, cowpea, bambara groundnut, soya, sesame) and average milk yield (in l/cow/d).

We performed variance analyses to test the significance of the differences between the 3 Ae clusters on the eight structure variables and the thirteen technical performance variables. Whenever a significant difference was found ($p < 0.05$), it was followed by a Newman Keuls test.

Ultimately, we sought to explain the performance of each Ae farming system cluster considering their structural characteristics and considering the intensification of synergies between the agro-sylvo-pastoral components of the system and by the establishment of more intense recycling processes often activated by the presence of livestock. To this end, we have schematized on figures the agroecological functioning of each agroecological farming system clusters (recycling of crops and livestock by-products, soil protection, spontaneous use of resources, cropping system bio-diversification and on limitation of industrial inputs). These diagrams represent the key elements of the Ae farming system cluster, completed with the data of each agricultural practices (means and standard deviation).

3 Results and discussion

3.1 A minority of farms standing at the top of an agroecology intensity gradient

A description of the 3 clusters of agroecological farming systems (Ae+, Ae+/-, and Ae-) based on 391 farms and their agricultural practices is presented in Table 2.

In Table 2, we arranged all 7 groups of farming systems according to an agroecology intensity gradient developed using the Ae scoring system proposed in the methodology. According to this system, groups G4 and G6, which respectively present Ae scoring of $+4.5$ and $+1.0$ (i.e., $+3.0$ weighted Ae score), are at the top of the agroecological gradient and constitute the Ae+ cluster (17% of farms). The G3 group, on the other hand, has the lowest Ae scoring (-10.5) and constitutes the Ae- cluster (25% of the farms).

Table 2 Overview of the 7 farm groups and the 3 agroecological farming system clusters arranged (from left to right) from least agroecological (Ae-) to most agroecological (Ae+) farming systems. Key: *TLU*, tropical livestock unit (1 TLU = head of cattle with a live weight of 250 kg); *DM*, dry matter; a, b, c, d, e: on the same line, values with different letters are statistically different and $p < 0.001$. (1) For G7, indicators 4, 13, and 14 were not calculated because these farms have no livestock; (2) scoring calculated on 12 indicators (1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, and 15); NB; an Ae score can also be calculated by considering the 15 indicators, weighting the scores by the number of indicators entered (12 for indicators 4, 13, 14) and 15 for the others. This changes the Ae scoring value of the farm group. However, that did not change the clustering. (3) Number of occurrences $Indic_i^G > 1.05 \times Indic_i$; (4) number of occurrences $Indic_i < Indic_i^G < 1.05 \times Indic_i$; (5) Nb occurrences $Indic_i^G < 0.95 \times Indic_i$; (6) Nb occurrences $Indic_i^G < 0.95 \times Indic_i$; scoring formula: Ae+ (coef. +1) + 0.5 × Ae+ (coef. +0.5) - 0.5 × Ae- (coef. -0.5) - Ae- (coef. -1).

N°	Farm group	Units	Indicator	G3	G5	G1	G2	G7 (1)	G6	G4	Means	Pr > F (model)
1	Number of farms	Agricultural practice	Number of trees/ha	97	130	57	15	25	28	39		
2	Maintenance of wooded areas on fields	Soil and Water conservation measures	Farmland under SWCM practices (%)	9 c	11 bc	10 c	11 bc	10 c	14 b	16 a	11.3	< 0.001
3	Agroecological tools and equipment	Agroecological tools and equipment	Proportion of agroecological tools and equipment (%)	28 b	49 b	23 b	21 b	37 b	39 b	86 a	41	< 0.001
4	Use of pasture to feed livestock	Use of pasture to feed livestock	Farm's grazing livestock (%)	56 bc	63 abc	73 a	52 c	32 d	78 a	70 ab	62	< 0.001
5	OM deposited by night-parked livestock	OM deposited by night-parked livestock	OM deposited by night-parked livestock (kgDM) / cultivated area (ha)	98 a	88 a	90 a	49 b	-	94 a	97 a	91	< 0.001
6	Mulch on cultivated area at dry season end	Mulch on cultivated area at dry season end	Mulch density (kgDM / ha)	795 b	369 b	410 b	184 b	689 b	4961 a	965 b	882	< 0.001
7	Organic fertilization of cultivated area	Organic fertilization of cultivated area	% of cultivated area	1506 b	1129 b	1299 b	1318 b	1054 b	1420 b	3355 a	1493	< 0.001
8	Cropping without herbicides	Cropping without herbicides	Cultivated area without any herbicides (%)	38 d	69 b	31 d	57 bc	29 d	90 a	48 cd	52	< 0.001
9	Minimum soil disturbance	Minimum soil disturbance	Cultivated area under no-till and direct seeding (%)	0 b	1 b	1 b	15 a	1 b	1 b	3 b	2	< 0.001
10	Cropping without mineral fertilizers	Cropping without mineral fertilizers	Cultivated area without any mineral fertilizers (%)	0 b	0 b	0 b	2 b	21 a	0 b	0 b	1	< 0.001
11	Legume crops cultivation	Legume crops cultivation	Cultivated area under legume crops (%)	23 de	15 e	68 a	37 bc	39 bc	29 cd	48 b	31	< 0.001
12	Fodder storage and preservation	Fodder storage and preservation	Stored fodder (kg) / cultivated area (ha)	13 c	13 c	50 a	31 b	28 b	14 c	24 b	21	< 0.001
13	Nourishing livestock without feed	Nourishing livestock without feed	Farm's livestock nourished without feed at all (%)	295 bc	503 b	666 b	471 b	87 c	1984 a	356 bc	539	< 0.001
14	Use of forages to supplement livestock feed	Use of forages to supplement livestock feed	Farm's livestock receiving forages (%)	94 ab	72 d	83 c	91 b	-	81 c	78 cd	83	< 0.001
15	Organic manure production in pens, pits, biogas	Organic manure production in pens, pits, biogas	OM produced (kgDM)/cultivated area (ha)	19 b	36 a	33 a	18 b	-	31 a	32 a	29	< 0.001
	Ae scoring and clustering farm groups (2)			392 b	645 b	664 b	617 b	985 b	2757 a	776 b	770	< 0.001
	Ae+ (coef. +1) (3)			0	2	4	4	4	6	8		
	Ae+ (coef. +0.5) (4)			1	2	0	0	0	0	0		
	Ae- (coef. -0.5) (5)			0	0	0	1	1	2	1		
	Ae- (coef. -1) (6)			11	8	8	7	7	4	3		
	Ae scoring/farm group			-10.5	-5.0	-4.0	-3.5	-3.5	1.0	4.5		
	Ae farming system clusters/farm group			Ae-	Ae+/-	Ae+/-	Ae+/-	Ae+/-	Ae+/-	Ae+		
	Ae score weighted of the cluster			-10.5	-4.5						+3.0	
	Agroecological intensity gradient			Ae- <-----Ae+/------> Ae+								

The other groups G7, G2, G1, and G5, which respectively present Ae scoring of -3.5 , -3.5 , -4.0 , and -5.0 (i.e. -4.5 weighted Ae score), constitute the intermediate cluster (Ae+/-: 58% of the farms).

3.1.1 Elements of discussion on the agroecological character of the three Ae clusters

Within the Ae+ cluster, the following agricultural practices contribute to the agroecological character of the system, with metrics that are very often significantly above average: (1) intensive storage of crop by-products for fodder purposes (agricultural practices N°12 and 14); (2) intensive and diverse methods of producing and using organic manure (N°5, 7 and 15); (3) higher use of spontaneous pasture to feed grazing livestock (N°4); (4) more densely grown wooded areas (N°1); (5) higher levels of cultivated area under soil and water conservation measures (field manure pits, grass strips, stone barriers; N°2); (6) higher levels of agroecological equipment and buildings (animal traction equipment, fodder sheds, organic manure production equipment; N°3); (7) higher cultivated areas under pulse crops (N°11). (8) higher cultivated areas crop without mineral fertilizers (N°10); (9) thicker mulch coverage in the dry season on cultivated areas (N°6).

The first two blocs of practices that underpin the combination between agriculture and livestock farming in agropastoral systems (storage of crop residues and use of organic manure) are well-known and recognized as important contributors to the intensification, resilience, and sustainability of mixed agro-pastoral systems (Schiere et al. 2002; Debray et al. 2019; Ayantunde et al. 2020; Rufino et al. 2021). They imply the simultaneous presence on the farm of significant numbers of animals and cultivated plots, which is why they are found on farms where these two activities are well developed.

However, our study provides new elements for characterizing Ae+ farming systems in the agro-sylvo-pastoral context of the West African savannahs:

1. The first one refers to the attention paid by Ae+ farmers to maintain on the cultivated fields a high density of wooded areas and a high level of soil and water conservation measures, to use intensively Ae agricultural tools, and to maintain a thick mulch on the cultivated areas. Incidentally, this last point somewhat flies in the face of conventional thinking regarding the theoretical conflict between livestock farming and plant cover, since it seems that these farmers are able to manage the trade-offs between optimizing the use of crop residues as a forage resource and soil coverage (Andrieu et al. 2015; Diarisso et al. 2016);

2. The second one relates to the livestock farming system's intensification in terms of animal feeding. The feeding system does not involve giving up grazing in favor of feed as some theories have suggested (Rufino et al. 2021), but instead simultaneously maintains grazing, a sustained use of stored dry fodder crop residues (straws and tops), and the use of animal feed within the Ae+ farms cluster.

3.1.2 Elements of discussion on the method used to develop the agroecological clusters

On the theoretical level, the suggested agroecology intensity gradient is admittedly somewhat simplistic since no threshold values are included in the indicators. Yet, it is quite possible that above and below threshold values, which remain to be defined, the increase or decrease in practices would become detrimental to the farming system. For instance, an excessive density of trees on the plots would make farming impossible; the total absence of grazing would seriously harm the well-being, nutritional status, and health of the animals; excessive organic manure or storage of fodder residues would lead to waste; the total absence of mineral fertilizers would be detrimental to the maintenance of soil fertility in the region. Consequently, for indicators that can vary from 0 to ∞ (trees/ha, kg manure per ha, kg stored fodder per ha, kg mulch/ha), we checked that the maximum values remained at commonly accepted levels, which is the case. For indicators expressed in % (developed fields, Ae equipment ownership rate, share of livestock receiving pasture, fodder or feed, area under no-till, under legumes, treated with mineral fertilizers, organic manure, herbicides), no published data is available. We have, therefore, taken the view that the greater the %, the stronger the Ae nature of the system. On a practical level, the method used to classify a large batch of farms (about 400) in 3 homogeneous Ae clusters with respect to 15 agricultural practices whose intensity increases the agroecological character of the system, by combining a multivariate analysis (ACP+ CAH) to an Ae scoring system, has proven to be effective and simple to implement. Moreover, the clustering was not affected by the number of indicators filled in (12 or 15). This is a positive point for the method, because it makes it possible to deal together with farms which do not have the same lists of agricultural practices.

3.2 In-depth analysis of agroecological farming system clusters

3.2.1 Structural features of the agroecological farming system clusters

The structural characteristics of each Ae cluster (Ae+, Ae+/-, and Ae-) are presented in the Table 3.

Table 3 Structural characteristics of the 3 agroecological farming systems clusters. Key: a; b; c; d: on the same line, values with different letters are statistically different and $p < 0.05$; 1 USD = 574

FCFA; Av (average values), figures in regular type; S. D. (standard deviation), figures in italics.

Agroecological farming system clusters		Ae–	Ae+/-	Ae+	Average	$Pr > F$ (model)
Number of farms	U	97	227	67		
Livestock	TLU	Av. 26 b	13 c	35 a	20	<0.0001
		<i>S.D.</i> 30	23	54	33	
Cultivated area	ha	Av. 8.5 a	9.1 a	7.0 a	8.6	0.134
		<i>S.D.</i> 7.9	7.7	7.1	7.6	
Cotton field area	%	39% a	40% a	27% b	38%	<0.0001
Maize field area	%	39% a	33% b	36% a	35%	<0.0001
Other cereals field area	%	7% b	6% b	13% a	7%	<0.0001
Legume field area	%	15% b	21% a	26% a	20%	0.004
Family members	U	Av. 12 a	13 a	13 a	13	0.682
		<i>S.D.</i> 8	9	9	8	
Number of family workers	U	Av. 6 a	7 a	6 a	7	0.445
		<i>S.D.</i> 5	5	6	5	
Hired agricultural workers & shepherds	U	Av. 0.3 a	0.2 a	0.4 a	0.3	0.061
		<i>S.D.</i> 0.5	0.6	0.7	0.6	
Number of workers/cultivated ha	U/ha	Av. 1.12 b	1.02 b	1.45 a	1.12	0.001
		<i>S.D.</i> 0.86	0.72	1.07	0.84	
Value of equipment & agricultural buildings	FCFA	Av. 1 408 041 a	1 345 617 a	1 613 955 a	1 407 084	0.463
		<i>S.D.</i> 1 564 743	1 452 668	1 848 177	1 553 432	
Value of non-Ae equipment & buildings	FCFA	Av. 732 990 a	619 383 a	607 463 a	645 524	0.703
		<i>S.D.</i> 1 320 647	1 088 912	1 294 313	1 184 266	
Value of Ae equipment & buildings	FCFA	Av. 675 052 b	726 233 b	1 006 493 a	761 560	0.001
		<i>S.D.</i> 427 215	528 625	959 911	612 935	

These structural data provide three major pieces of information on the three Ae clusters. First, livestock farming is significantly more prominent in Ae+ cluster compared to Ae–, and Ae+/- (respectively, 36, 26, and 13 TLUs/farm). Second, the level of Ae equipment and buildings (animals and animal power equipment, fodder storage buildings, organic manure production infrastructure) is significantly higher in Ae+ farms, compared to Ae+/- and Ae– ones (respectively, 1006 vs 726 and 675 kFcf/farm). Thirdly, Ae+ workforce/ha ratio (1.45) is significantly higher than the ratio of Ae– (1.12) and Ae+/- (1.02). This reflects a trend towards a larger labor force in the Ae+ farming system cluster.

In terms of cultivated area, Ae+ has a lower value compared to Ae– and Ae+/- (respectively, 7.0 vs 8.5 and 9.1 ha) as it is mostly made up of livestock-oriented farmers. Farms with the largest cotton plots are found on the Ae– (39% of the cultivated area) and Ae+/- (40%) clusters side, and only 27% for Ae+. This importance of cotton among the Ae– and Ae+/- explains why these farmers use more mineral fertilizers than the Ae+, as the cotton company provides it in advance at the beginning of the cropping season. Ae+ farms have larger cultivated areas under other cereals (13% of the

cultivated area in sorghum, millet, rice) and legumes (26%) compared to Ae– (7% for other cereals and 15% for pulses) and Ae+/- (6% for other cereals and 21% for pulses).

In terms of “number of family members” and “hired agricultural workers and shepherds,” there are no differences between the 3 clusters.

Some authors argue that in savannah areas, agroecology is often adopted for want of anything better by farmers with little capital (livestock, land) and limited financial means, in other words, with only their own labor power to draw upon (Djamen Nana et al. 2015; Koutou et al. 2016; Berre et al. 2022). Our findings tend to show the opposite. Within the study area, the most agroecological farmers (Ae+) are in fact those who rear the most livestock, use the most agricultural Ae tools and equipment, and have a workforce (familial and hired) of comparable size to other clusters; in other words, they belong to the most affluent segment of the population. These are actually proactive farmers who optimize synergies between agriculture and livestock farming. Ouédraogo (2012) offered a similar conclusion in an ex-ante assessment on the uptake of conservation agriculture in the same region, in which his results showed that crop-livestock-oriented farmers were most prone to embrace this practice

because of the means at their disposal (equipment, livestock, workforce).

Now the reasons why Ae+ farms are in the minority in the study area (17% of farms) become clearer. This distribution between Ae+, Ae+/-, and Ae- farms is primarily due to the fact that the Ae+ group includes a large proportion of farms with above-average financial resources that have been able to invest in equipment and livestock, and we know that there are few of these wealthier farms in the area (Vall et al. 2006, 2017, 2019; Berre et al. 2022). It is also possible that the large-scale promotion, over the past 50 years, of a conventional intensification model of cotton farming, (intensification based on inputs that are relatively easy to acquire via input credit schemes; Ripoche et al. 2015), has led to a majority of farmers to 1) disregard value-adding practices using crop and livestock by-products recycling; 2) invest little in the soil and water conservation measures and in the maintenance of wooded areas in the cultivated areas. Our data clearly shows that the farmers most focused on cotton production stand mainly on the Ae- and Ae+/- clusters side (see Table 3). While some, perhaps many, may not have done so due to lack of resources. There is little doubt that many of the farmers have been influenced by this development model, which seeks to solve everything through the use of inputs and to disregard the potential offered by the many different recycling practices. Lastly, it is possible that Ae+ farms were more affected by R&D programmes focused on optimizing synergies between crops, livestock, and trees, because these larger farms, led by active managers labeled as “champions,” were more targeted by R&D projects.

3.2.2 Technical performances of the agroecological farming system clusters

Some technical performances of each Ae clusters (Ae+, Ae+/-, and Ae-) are presented in Table 4. For all crops, the yields of Ae+ cluster (in kgDM/ha of grain) are higher than average and, therefore, higher than Ae- and Ae+/- clusters, but the difference is only significant for maize, millet, and cowpeas due to intra-cluster yield heterogeneity. For milk production, the yield (in l/cow/day) of Ae+ is significantly higher compared to Ae-, and Ae+/- . We, therefore, sought to explain why Ae+ farms perform better.

3.2.3 Livestock contribution to crop-livestock by-product recycling, a major factor for agroecology

Figure 4 shows the synergies between the 15 agricultural practices studied, their level of intensity, and the crop-livestock by-product flows they generate in the 3 Ae clusters. The better technical performance of the Ae+ cluster can be explained by a combination of systemic and structural factors.

1. Compared to Ae- and Ae+/- farms, Ae+ farms call upon more labor (the number of workers per hectare is significantly higher) for additional tasks such as transport, conditioning and use of fodder and manure, and livestock herding and feeding. But the difference is not substantial and is mainly provided by the family workforce (which does not increase costs but can sometimes draw young people away from school). Ae+ farms also call upon more agroecological equipment, buildings, and energy sources (draft animals, animal power equipment, fodder sheds, manure pits), which require additional financial resources;
2. Ae+ farms store and produce significantly more fodder and organic manure due to their larger livestock populations, greater infrastructure for storage and production of organic manure, and more diversified organic manure production practices (field grazing, or production in pits, pens, biodigesters);
3. Ae+ farms invest more in the development of their fields and in ensuring a better organic and water status of the soil through more densely grown wooded areas (which increases root turnover and rhizodeposition), through the implementation of a greater number of small-scale soil and water conservation measures in the fields (compost pits at field edges, grass strips, and stone barriers) that reduce water and nutrient runoff, and through better soil protection with thicker mulch on cultivated area;
4. Ae+ farms use fairly similar (although slightly lower) amounts of synthetic inputs (mineral fertilizers, herbicides) compared to Ae- and Ae+/- farms, while still using local resources such as spontaneous grazing for livestock feed, as well as part of the crop residues to cover and protect cultivated land.
5. Lastly, Ae+ farms' livestock management methods combine mobility under the supervision of shepherds over the territory (through daily grazing on community rangelands and harvested fields) with time-limited stall housing, allowing for better control of fodder and feed distribution, and greater dung recovery. With this type of livestock farming, a larger share of spontaneous or cultivated plant biomass (natural hay and crop residues stored, then provided as fodder to livestock in stalls) and dung (to produce manure) can be optimized.

It, therefore, appears that livestock farming that combines grazing and stall housing and the spread of farm-wide storage and recycling devices for livestock and crop by-products (fodder sheds, pits, pens, biodigesters, wooded areas) and devices aimed at slowing down water and nutrient runoff (stone barriers, grass strips, small dikes) are good catalysts for agroecology in these West

Table 4 Crop yields and milk yields of the 3 agroecological farming systems clusters. Key: a; b; c; d: on the same line, values with different letters are statistically different and $p < 0.05$; 1 USD = 574 FCFA; Av (average values), figures in regular type; S. D. (standard deviation), figures in italics.

Cluster of agroecological farming systems			Ae–	Ae+/-	Ae+	Average	$Pr > F$ (model)
Cotton	Kg/ha	Av.	1037 a	1045 a	1119 a	1052	0.595
		<i>S.D.</i>	340	279	473	321	
Maize	Kg/ha	Av.	1789 b	2268 b	3241 a	2 312	0.008
		<i>S.D.</i>	745	1877	6104	2 944	
Red sorghum	Kg/ha	Av.	715 a	777 a	1048 a	819	0.333
		<i>S.D.</i>	491	748	824	699	
White sorghum	Kg/ha	Av.	688 a	775 a	1163 a	877	0.085
		<i>S.D.</i>	546	322	1234	768	
Millet	Kg/ha	Av.	735 b	823 b	1250 a	908	0.003
		<i>S.D.</i>	418	432	589	505	
Rice	Kg/ha	Av.	1745 a	2141 a	2666 a	2 168	0.314
		<i>S.D.</i>	1157	1265	2765	1 668	
Groundnut	Kg/ha	Av.	753 a	765 a	828 a	773	0.805
		<i>S.D.</i>	569	489	498	506	
Cowpea	Kg/ha	Av.	273 b	437 a	473 a	412	0.006
		<i>S.D.</i>	143	305	275	283	
Bambara groundnut	Kg/ha	Av.	769 a	360 a	796 a	560	0.248
		<i>S.D.</i>	667	292	885	585	
Soya	Kg/ha	Av.	780 b	833 b	1071 a	856	0.151
		<i>S.D.</i>	382	524	1 001	595	
Sesame	Kg/ha	Av.	246 a	374 a	348 a	335	0.402
		<i>S.D.</i>	313	328	368	333	
Milk	l/cow/day	Av.	0.4 b	0.2 c	0.8 a	0.4	<0.0001
		<i>S.D.</i>	0.5	0.4	1.5	0.8	

African agro-sylvo-pastoral systems. These new forms of livestock farming and crop-livestock by-products recycling emerge as important agroecological levers that bring into play the biotechnical principles of recycling, and synergy, which lie at the heart of agroecology at production system level (Wezel et al. 2020).

Ae+ farms look promising in terms of production performance (yields, Table 4), recycling of livestock and crops by-products, and soil fertility maintenance. But they are still few and far between, and it seems appropriate to raise the question as to what would happen if Ae+ systems were to spread widely.

The food system would undoubtedly benefit. By providing better yields, local production would increase, which in turn would help to improve food self-sufficiency in West African countries, without increasing production costs since the level of input use in such systems is more or less unchanged, and the additional workforce is family-based.

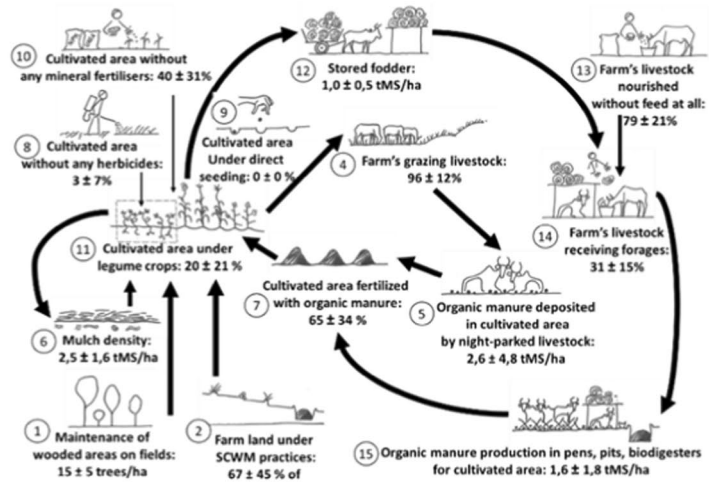
However, for good governance and sustainable management of natural resources in the territories, the unbridled increase in livestock numbers could quickly become a problem if pastoral resource management practices and livestock mobility are not regulated or even gradually reformed. Uncontrolled livestock expansion would indeed soon lead to multiple problems in terms of meeting the food and

nutritional needs of the animals, and uncontrolled grazing would have detrimental effects on spontaneous vegetation and soils (reduction in vegetation density, increased soil erosion by wind and water) (Ibrahim et al. 2010; Berre et al. 2021). The management of livestock and agricultural activities in open shared areas is not straightforward and can potentially lead to conflicts (Vall et al. 2011; Koutou et al. 2016). The challenge would be to develop livestock farming while controlling livestock mobility with rules recognized by the population and maintaining balanced livestock/crop ratios at farm and territory levels in order to produce fodder in sufficient quantity and quality, as well as a significant quantity of quality manure (Vall et al. 2015).

Regarding ecosystem health, the fact that ruminant livestock farming and organic manure production processes are important sources of greenhouse gas emissions should also be considered, especially if these systems are kept wide open and if the provided feed rations are highly methanogenic. To mitigate this, innovation would be needed in order to develop more enclosed and, therefore, more efficient manure production systems (such as biodigesters) as well as feeding practices based on optimizing the use of fodder resources, with a focus on more digestible and less methanogenic resources. This would optimize

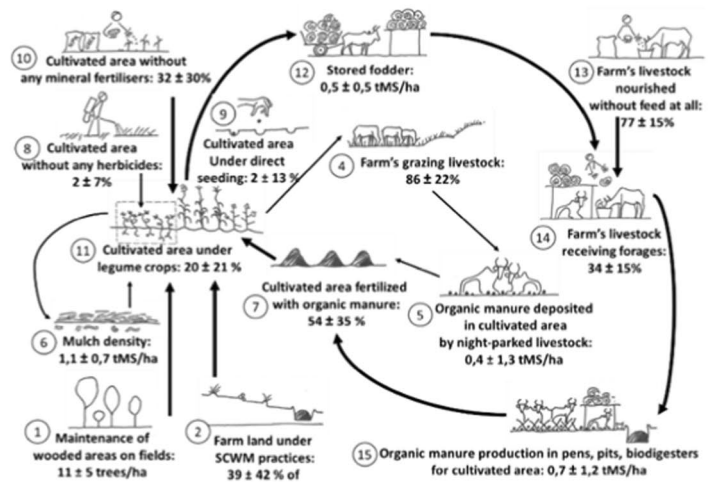
Ae+ farming system

3
Proportion of agroecological tools and equipment: 73 ± 25 %



Ae+/- farming system

3
Proportion of agroecological tools and equipment: 62 ± 28 %



Ae- farming system

3
Proportion of agroecological tools and equipment: 56 ± 25 %

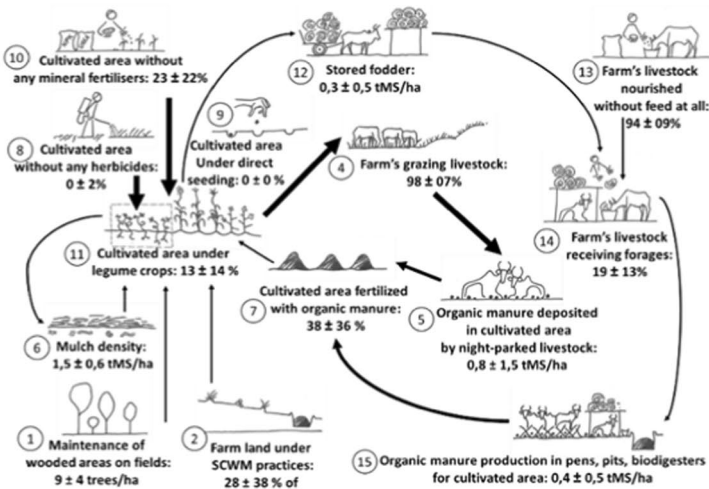


Fig. 4 Schematic diagram of farming system with high (Ae+), medium (Ae+/-), and poor (Ae-) level of agroecology (key: arrow thickness is proportional to the intensity of crop-livestock by-products flows).

the role of ruminant livestock farming in GHG emission mitigation strategies in agro-sylvo-pastoral areas (Diogo et al. 2013; Assouma et al. 2019).

4 Conclusion

The findings of this study show, for the first time, that crop-livestock synergies and by-product recycling are major factors for agroecology of agro-sylvo-pastoral systems. Evidence are made through quantitative metrics based on a large farm sample.

The method used to analyze the diversity of farming systems and to characterize Ae clusters is easy to replicate in other situations: on other agricultural systems, with other sets of agricultural practices, on a territory of comparable dimension. The basis of this approach lies in identifying a concise and meaningful set of quantitative indicators for agricultural practices. When these indicators are implemented effectively, they have the potential to enhance the agroecological nature of the agricultural system.

In the agro-sylvo-pastoral context of Western Africa Savannah, the most agroecological agricultural systems (Ae+) are characterized by the importance of livestock, by its multiple functions in recycling and recovering crops and livestock by-products in fodder, organic manure, and mulch. These recycling practices are facilitated in Ae+ farms compared to Ae- and Ae+/- farms by better rates of equipment and tools for transport and storage of crops and livestock by-products, by better soil water and crops residues conservation measures, and by better maintenance of the wooded park on the cultivated fields. This set of practices which tend to close the system produces a systemic effect which has a positive impact on agricultural yields and on the whole ecosystem (with a possible improvement of the C and water balance that would need further research to be proven).

However, Ae+ farming systems, although promising, are still marginal today (17% in the study area). Their expansion and replication, which could bring benefits to food systems, would also give rise to additional challenges related to sustainable resource management, governance in the territories, and viability. These challenges are key issues that call for further research to better understand the current dynamics and propose sustainable solutions.

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Availability of data and material The datasets generated and/or analyzed during the current study are available from the corresponding author on a reasonable request.

Code availability Not applicable

Declarations

Ethics approval The manuscript does not contain clinical studies or patient data.

Consent to participate Verbal informed consent was obtained prior to the interview of the Koumbia farmers.

Consent for publication The interviewed farmers have consented to the submission of the results of this study to the journal.

Competing interests The authors declare no competing interests.

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