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Contribution of traditional goat farming systems to the sustainable intensification of smallholder agriculture in sub-Saharan Africa: The example of the western part of the Democratic Republic of Congo

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ABSTRACT

Integrated crop-livestock systems (ICLS) increase smallholder yields and environmental benefits by enabling positive interactions between livestock and crops. As goat farming is popular in Africa, in this study, we aimed to characterise goat-rearing systems and further understand the role of goat management and the relevant drivers in ecological intensification processes. We conducted an exploratory snowball sampling of 147 goat breeders in the western provinces of the Democratic Republic of Congo (DRC). The smallholders used five agroecosystem components: animal husbandry (100%), croplands (100%), rangelands (73%), fishponds (22%) and beekeeping (2%). In 97% of the cases, the agroecosystem of a single farmer was fragmented, with an average of 3 ± 1 plots of land. In 31% of the cases, the plots of land were 2.5 km apart from the others, 40% were 2.5–5 km apart, and 29% were over 5 km apart. The short distance (<2.5 km) between animal husbandry land and cropland was positively associated ($p < 0.05$) with the use of manure as fertiliser and crop residues as animal feed, contributing to ecological intensification. Additional factors (training, breeding pigs and goats, vegetable gardening) were significantly associated ($p < 0.05$) with the aforementioned agroecological practices. Consequently, three categories of goat breeders were distinguished. The first group, not committed to ecological intensification, had free-grazing goats. The second group also had free-grazing goats, whereas the third tethered or kept goats in confined areas, and both were committed to ecological intensification. Traditional goat farming contributes to ecological intensification when smallholder farmers follow best management practices.

1. Introduction

The world population is constantly increasing, driving food demand (Bourban, 2019) and exerting enormous pressure on natural resources (Syampunga et al., 2021). In this context, tropical humid savannahs are pivotal for agricultural intensification but are also highly vulnerable (Boval et al., 2017; Kuyah et al., 2021) because they usually develop in nutrient-deficient and acidic soils (Faber-Langendoen, 2020). In numerous countries in sub-Saharan Africa (SSA), crop farming is traditionally practiced using the slash-and-burn method, in which land is opened by fire, cropped for 3–4 years and then left for a long fallow period lasting several decades until fertility is restored (Van Vliet et al., 2012; Thomaz, 2017; Tang and Yap, 2020). This method of managing soil fertility no longer operates efficiently because the fallow periods, due to the pressure on land, are getting shorter. Therefore, if smallholder farmers cannot afford to buy imported fertilisers, they will face decreasing yields, subjecting them to the risk of poverty and making them more vulnerable to hazards, including climate change. Thus, affordable technical solutions are required to intensify smallholder agriculture in sub-Saharan Africa while minimising negative environmental impacts.

Several studies suggest agroecological solutions to limit the loss of soil fertility and soil health by enhancing ecological services (Bonaudo et al., 2014; Grillot et al., 2018; Stark et al., 2018). Ecological services refer to the various natural functions provided by ecosystems, such as cycling nutrients and sequestering carbon in the biomass of a given agroecosystem (Ghaley et al., 2014; González-De-Molina and Guzmán Casado, 2017). In addition, Ogisi and Begho (2023) reported that, in

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response to climate change, agroecological solutions enhance the resilience and adaptability of agroecosystems. In this regard, to achieve sustainable agriculture, various agroecological solutions, such as integrated crop-livestock systems (ICLS), are recommended (Kuyah et al., 2021; Ogisi and Begho, 2023).

The goat, a significant livestock species in rural regions of SSA (FAOSTAT, 2020; Gracinda et al., 2021), has the potential to play a crucial role in ICLS. Better integration of crop production and goat rearing could lead to more sustainable farming for low-income smallholder farmers. First, breeding small ruminants is less demanding in terms of inputs (Dossa et al., 2015; Ashit et al., 2020). Goat farming is feasible for a wide range of temperatures and drought conditions (Sejian et al., 2021) and offers numerous economic and social benefits (FAO, 2015), while simultaneously enhancing smallholder resilience (FAO, 2021), with little effort required (Shivakumara et al., 2020; Kumar et al., 2021; Sejian et al., 2021). Second, goats have a highly capable digestive system that can convert poor-quality forage, such as savannah grass and crop residues, into valuable food products and manure for soil health improvement (Lamming, 2001). Goat rearing could be a valuable component of biodiversity that strengthens ecological intensification, which is defined as a set of nature-based solutions to limit high imported inputs and negative environmental impacts in agriculture by enhancing ecosystem services such as nutrient and organic matter cycling (González-De-Molina and Guzmán Casado, 2017; Struik and Kuyper, 2017; Kleijn et al., 2019).

However, ecological intensification involving goat farming has not yet been reported (Syampunga et al., 2021) and therefore needs to be addressed (Boval et al., 2017; Sejian et al., 2021). Prior to that, the misunderstanding of indigenous practices and the knowledge of traditional goat breeders, which support the ecological intensification process, should be explained (Altieri et al., 2012). Therefore, we conducted the present study in rural areas in the western part of the Democratic Republic of Congo (DRC), with the following aims: (1) to identify the existing components of the agroecosystem in which goats are reared; (2) to describe its spatial structure at the farm or village level; (3) to characterise traditional goat breeders, their farming practices and the associated factors that can promote ecological intensification and (4) to develop a conceptual model based on these farming practices.

2. Materials and methods

2.1. Study area

This study was conducted in four provinces in the western DRC, namely Kinshasa, Congo Central, Kwilu and Kwango, to assess diverse goat breeder practices, forages, agroecosystem components and their interactions. The study area covered Kinshasa, Congo Central (4–5° S and 15–17° E) (Biloso Moyenne, 2008) and Kwango, Kwilu (4–8° S and 16–20° E) (Omasombo-Tshonda et al., 2012).

The dominant ecosystem type in the study area is savannah, interspersed with gallery forests along rivers and wetlands and forest patches at the periphery of Kinshasa Province (Biloso Moyenne, 2008) in the eastern part of Kongo-Central (Lugangu et al., 2018), Kwilu (Fonds National REDD, 2018) and Kwango (Omasombo-Tshonda et al., 2012). Because of the positive correlation between rainfall and plant biomass productivity (Marín et al., 2001), these vast savannahs constitute an important fodder reservoir that enables extensive goat breeding. According to the International Vegetation Classification (IVC), the study area's biome belongs to the "West-Central African Mesic Woodland and Savannah" division, as noted by Faber-Langendoen (2020).

The climate is Aw4, according to Köppen's classification (Lohmann et al., 1993). The region has a tropical-humid Sudanian climate with two contrasting seasons; a 4-month dry season (that extends from mid-May to mid-September in the Kinshasa, Kwilu and Kwango provinces and can last for 5 months, extending until mid-October in the Kongo Central province) and an 8-month rainy season. The average annual temperatures range between 25 and 28 °C, and the average annual rainfall is approximately 1400 mm (Biloso Moyenne, 2008; Omasombo-Tshonda et al., 2012; Lugangu et al., 2018).

2.2. Sampling and data collection

A total of 147 smallholder farmers involved in goat and crop farming were surveyed using a snowball sampling technique, as previously used by Stark et al. (2016). The sampling entailed making contact first and then gathering more contacts from those already obtained. This technique enabled us to contact the smallholder farmers increasingly involved in goat and crop farming in a given territory or village.

Survey data were collected using a questionnaire on the KoboToolbox interface (OCHA, 2019) and by interviewing goat smallholders who were also involved in crop farming. The data collected included personal information (e.g., age, gender, education level, training), socioeconomic information (e.g., financial sources, whether production is market-based or not, familial or salaried labourers, land rented or owned) and agrotechnical information (e.g., breeding and cropping methods).

2.3. Statistical analysis

Multiple correspondence analysis (MCA) was performed using FactoMineR to identify different goat farming systems. This statistical process involved crossing personal, socio-economic and technical variables from the goat farmers surveyed as a first step to identify those variables that are most strongly correlated ($p < 0.05$) with the factor map axes of the MCA. Thus, the data collected were summarised as active variables (Renisio and Sinthon, 2014, Table 1), enabling discrimination among different types of goat farms.

These active variables were used automatically to process a hierarchical ascending classification (HAC) with the FactoMineR package. Based on this, we constructed a typology of goat farms, based on their farming practice similarity, which promotes or not an ecological intensification of agroecosystem components at the farm or the village scale.

These agroecosystem components and their spatial structures were identified using standard descriptive statistics performed with IBM SPSS Statistics 20.0 regarding their occurrence among goat farmers. Furthermore, the variables significantly associated ($p < 0.05$) with the farmers' practices that are expected to promote ecological intensification among these agroecosystem components, at the farm or village scale, were identified using the Chi-square test. Finally, the use of these traditional farming practices by goat breeders enabled the construction of an agroecological intensified model, based on various interactions between goat herds and different agroecosystem components.

3. Results

3.1. Identification of agroecosystem components and their spatial structure

Five components of the agroecosystem were identified among the goat breeders. The (1) animal husbandry and (2) cropland components were exploited by all goat breeders surveyed (100%), whereas 73% exploited the rangeland component (3). Besides these three major components, (4) fish farming (22%) and (5) beekeeping were observed at a marginalised rate (2%).

The spatial structure of the agroecosystem was fragmented in nearly all cases (97%), with an average of 3 ± 1 plots per farmer. For 31% of the goat farmers, each of their plots did not exceed 0.5 ha, whereas 45% had plots that were 0.5–1 ha each, and 24% had plots over 1 ha. The distances between the plots were < 2.5 km for 31% of the goat farmers, 2.5–5 km for 40% and > 5 km for 29% of the goat farmers.

3.2. Goat farming practices that can promote ecological intensification

The conceptual model (Fig. 1) illustrates the interactions between

Table 1
Variables of the goat breeder farms used in the multiple correspondence analysis.

Variable	Modality/Label
Age of surveyed farmer	Inf36 = less than 36 years
	36a45 = from 36 to 45 years
	Sup45 = more than 45 years
Gender of surveyed farmer	F = female
	H = male
Fish farming activities	Absent
	Present
Sheep breeding	Absent
	Present
Cow breeding	Absent
	Present
Pig breeding	Absent
	Present
Poultry breeding	Absent
	Present
Rabbit breeding	Absent
	Present
Guinea pig breeding	Absent
	Present
Funding source	Self-funding
	Self-funding and external funding
Product destination	Market and self-consumption
	Market
Land structure	Fragmented land
	United land
Breeding mode	Rambling
	Enclosure rearing
	Tethering
Free-ranging feeding	No free-ranging feeding
	Free-ranging feeding
Feeding with forage available in the fenced area	No feeding with forage available in the fenced area
	Feeding with forage available in the fenced area
Feeding with crop residues	No feeding with crop residues
	Feeding with crop residues
Veterinary products	No veterinary products
	Veterinary products rarely used
	Veterinary products regularly used
Vegetable gardening	Absent
	Present
Chemical fertiliser use	No use of chemical fertiliser
	Use chemical fertiliser
Manure use	No use of manure
	Use of manure

goat herds and different agroecosystem components through goat farming practices (Table 2).

The survey results revealed that 50% of the farmers used manure from their livestock to fertilise their croplands. All goat farmers who had a formal agricultural education or 55% of them who had been trained by NGOs were more likely to use on-farm animal manure to fertilise their croplands. Using animal manure was found among 67% of the farmers who reared both pigs and goats on the same site, 55% of those who had built a night shelter and even 82% of those who had a vegetable garden less than 2.5 km away from the livestock farm (65%).

Regarding animal feed, 53% of the goat farmers used crop residues to feed their livestock. All smallholder farmers keeping goats in confinement and 95% of those keeping goats tethered in pasturelands used this management practice, which was found among 66% of the goat farmers in urbanised areas. This farming practice was also common among 70% of the goat farmers who had livestock and crops within 2.5 km of each other. In addition, 75% of the female farmers fed crop residues to goats.

In terms of sourcing animal manure, 96% of the goat farmers did not import manure from neighbouring farms to fertilise their croplands, whereas 4% did. The practice was more common among the goat farmers who had received formal agricultural training or had a vegetable garden. Also, 25% of the farmers collected crop residues from neighbouring fields to feed their goats. Importing crop residues was most practiced by 85% of the farmers keeping their goats tethered and 65% of those keeping them in confined areas. In addition, 97% and 100% of the farmers who fed crop residues to their livestock collected sweet potato and cassava residues, respectively.

The provision of livestock manure to neighbouring croplands was also observed among 52% of the smallholder farmers. This practice was common among older farmers (61% over 45 years of age) and among 80% who reared goats in confinement.

3.3. Characterisation of the traditional goat farmers

Fig. 2a shows the initial step of the characterisation of goat farmers. It illustrates the most discriminating variables, which explained approximately 26% of the total variability among the goat farmers when all the variables relevant to the farming practices were projected onto the first and second dimensions of the factor map.

The first dimension (Fig. 2a) indicates that the goat rearing and feeding methods allowed clustering goat farmers confidently because of their highest correlation ratios on the factor map axis (0.735 and 0.727), followed by feeding goats with crop residues and forage available in fenced areas, with medium correlation ratios (0.483 and 0.447). In the second dimension (Fig. 2a), the most discriminating variables were “the use of manure” and the crop type (vegetable gardening), with correlation ratios of 0.436 and 0.412, respectively, on the second axis of the factor map.

Regarding smallholder rearing and cropping methods, the MCA (Fig. 2b) highlights that the farmers who allowed their goats to graze freely without providing crop residue supply were unlike those who kept goats confined or tethered and fed them crop residues or forage present in the fenced areas. The second dimension separates farmers who owned vegetable gardens and used animal manure from those who did not.

3.4. Typology of goat breeding systems

Based on the most discriminating variables (“feeding method”, “breeding method”, “type of crop” and “using animal manure”), as previously presented in the factor map (Fig. 2a), the hierarchical ascending classification distinguished three main clusters of goat farmers. Fig. 3 illustrates these clusters, and Table 3 outlines their key characteristics.

Table 3 shows that in Cluster 1, 95% of the farmers reared goats using free-roaming methods, 98% allowed free grazing on natural grasslands, and 80% did not provide crop residues. Additionally, 96% of these farmers did not use animal manure as fertiliser, and 89% did not have a vegetable garden.

In Cluster 2, all the farmers reared their goats using roaming methods, and free grazing on natural pastures was their feed method, whereas 70% of them did not provide crop residues. However, 91% used animal manure as a fertiliser for their vegetable gardens, and 98% of the farmers owned vegetable gardens.

Cluster 3 was marked by 51% of farmers who kept their goats tethered and 46% that confined them inside a fenced area. Within cluster 3, 90% of the farmers used crop residues, and 64% used forage from the enclosed area as their primary sources of animal feed.

4. Discussion

The integration of crop and livestock farming is a pillar of sustainable agriculture as ecological intensification processes occur between agroecosystem components, interacting with and enhancing ecosystem services such as nutrient cycling as well as food and fodder supply. This, in turn, limits the need for external inputs. At the farm and village scale in the western DRC, ‘livestock’, ‘cropping land’ and 'savannahs' were the main components of the agroecosystem exploited by goat breeders. Livestock and crops were mainly grown on natural savannahs or fallow land, with little or no inputs. Such extensive farming, reported by Vall et al. (2014), is widespread in rural areas of the DRC

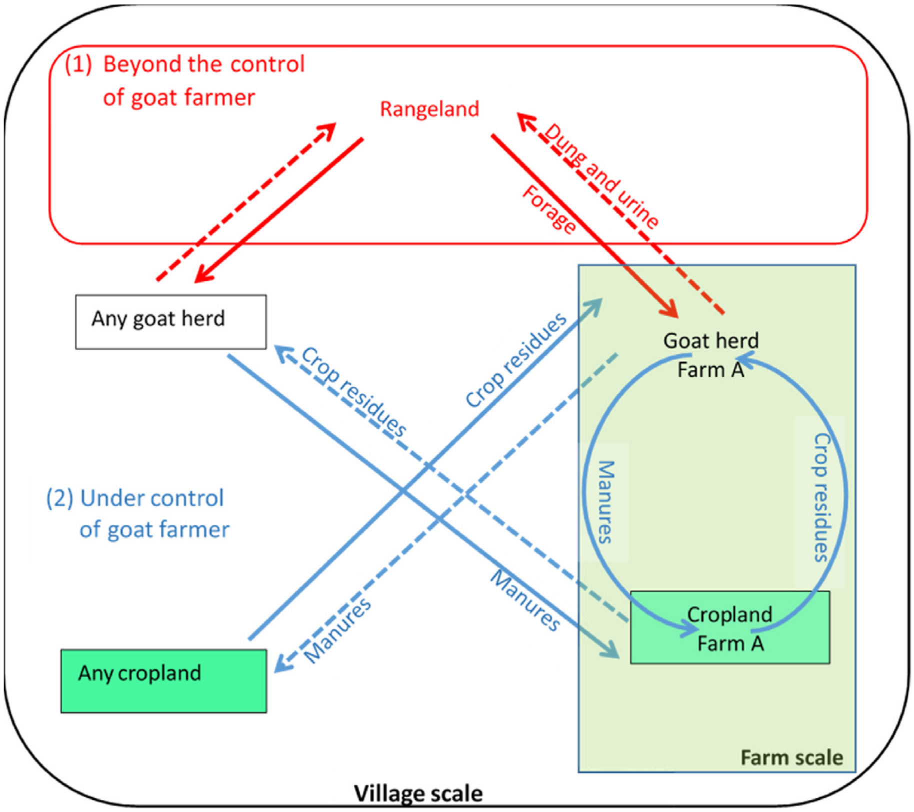

Fig. 1. Agroecological intensified model of the interactions among the three major components of agroecosystem, namely goat herds, rangelands and croplands.
The circular arrows indicate the intra-farm interactions under the control of the goat farmers' practices (2). For example, inside a single farm (farm A), the use of crop residues as animal feed and animal manure as soil fertiliser is the way to sustainable intensification. The straight continuous and the stippled arrows refer to the import and export of manure, crop residues, or forage inside and outside a farm (e.g., farm A). These interactions could be under the control of the goat breeder (2) or beyond the control (1) of the goat breeders' practices.

Table 2
Goats farmers' practices promoting nutrient flow between the animal and crop components of the agroecosystem at farm and village scales.

Farming practices	Flow orientation	Users (n)	(%)
Use of on-farm animal manure as soil fertiliser	Internal flow	73	50
Use of on-farm crop residues as animal feed	Internal flow	78	53
Export of animal manure as fertiliser for neighbours' croplands	Exportation (out-flow)	77	52
Export of crop residues as animal feed for neighbouring herds	Exportation (out-flow)	6	4
Import of animal manure from neighbouring herds as cropland fertiliser	Importation (in-flow)	6	4
Import of crop residues from neighbouring cropland as animal feed	Importation (in-flow)	37	25

(Omasombo-Tshonda et al., 2012; Mafwila et al., 2018) and elsewhere in SSA (Thornton et al., 2011; Losch, 2016) and practiced by most farmers for subsistence and income generation. In this regard, 73% of the goat farmers used the savannah as the main source of animal feed. Thus, the savannah component represents the largest feed support for goat farming because of the tropical climatic conditions, allowing high forage biomass production, similar to the findings of Marín et al. (2001) for the agroecosystems of tropical America.

Natural savannah areas provide several ecosystem services, including food provision for humans and livestock, carbon sequestration and the provision of habitat for numerous species (Ghaley et al., 2014). The diversified plant species and their high biomass productivity in the tropical savannah of the western DRC provide goats with most of the necessary feed resources and reduce the dependence of goat farmers on external feed resources. This ecosystem service by the savannah contributes to ecological intensification (Struik and Kuyper, 2017). In return, goats contribute to the health of the savannah's soil by leaving behind droppings, increasing the organic carbon and total nitrogen levels in the soil. N'Dri et al. (2023) reported a positive effect of animal manure on soil health.

Besides the three major components, namely livestock, crop farming and savannah, 22% and 2% of goat farmers owned fishponds and kept honeybees, respectively, ensuring additional components for their agroecosystems and contributing to the diversification of their farming activities. Beekeeping in the acacia agroforestry site of the Batéké upland (Bisiaux et al., 2012), an exemplified ecological intensification performed by goat farmers, enriches the savannah with woody species such as acacia. Acacia leaves provide fresh green fodder throughout all seasons, being particularly important during the dry season, when grasses do not produce sufficient forage biomass for livestock due to limited rainfall. Although production diversification can ensure the resilience and sustainability of agroecosystems through diverse positive interactions among their components (Vall et al., 2012; Mafwila et al., 2018), the goat farmers' practices did not reveal any direct interactions between fishponds and goat rearing or crop farming that lead to sustainable intensification. In China for instance, Liu (2023) reported mulberry-based fishponds and fish farming in paddy fields. However, in the DRC context, to experience ecological intensification, smallholder farmers could be trained in fertilising fishponds with goat manure to promote the growth of planktonic algae to feed fish.

The fragmentation of the agroecosystem and the removal of its components impede ecological intensification. In this study, each component rarely exceeded an area of 1 ha, as also reported by Mafwila et al. (2017) for the outskirts of Kinshasa, by Vall et al. (2014) for small family farms in Madagascar and by experts of the Food and Agriculture Organization of the United Nations (FAO, 2017). Consequently, the remoteness of agroecosystem components presents an additional difficulty for their connection as smallholder farmers could not easily transport heavy animal manure or crop residues. Thus, remoteness impairs positive interactions and nutrient flow among fragmented components by limiting their direct connection. As the nutrient flow on-farm is an

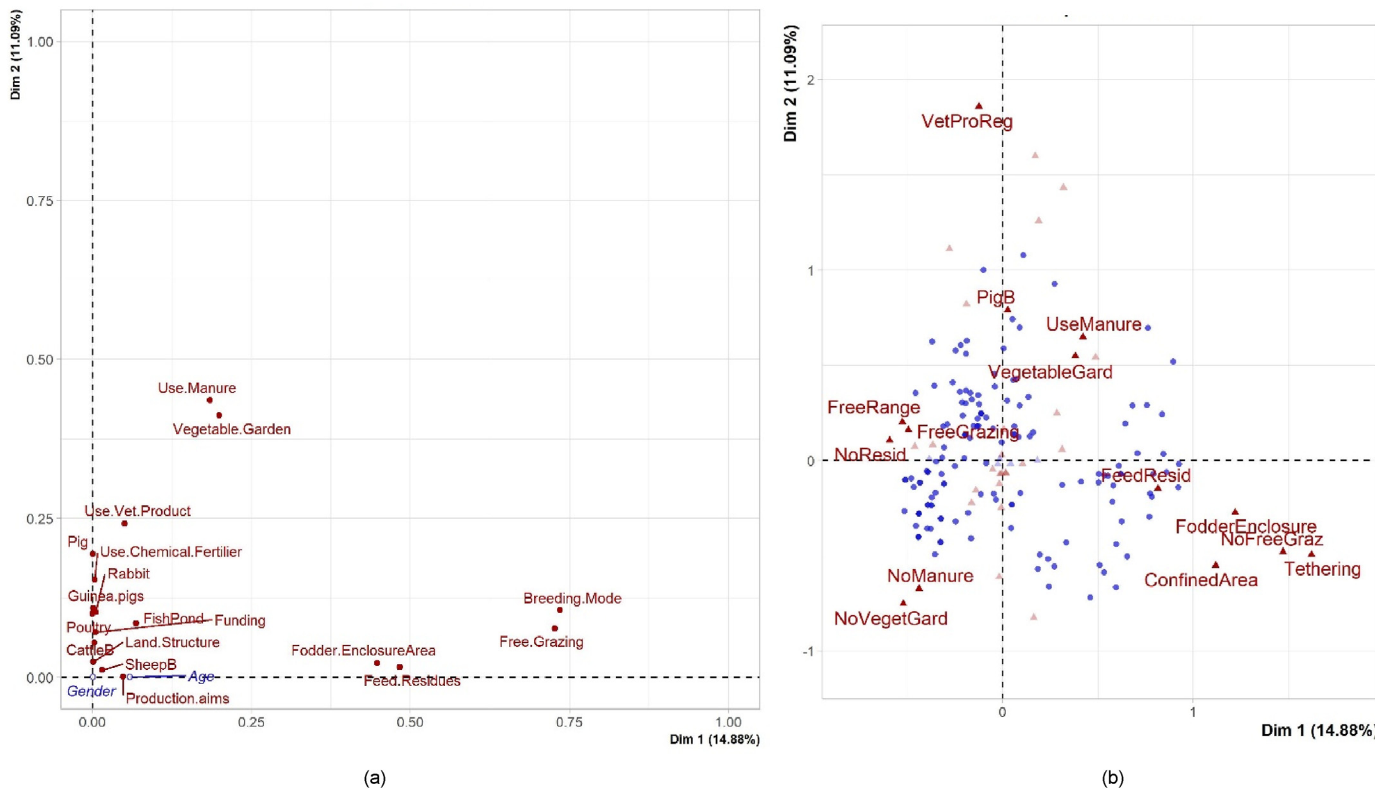

Fig. 2. Fig. 2a. Graph of variables, Fig. 2b. Graph of the variables' modalities
The graph of the variables (2a) illustrates the level of correlation of farming practice variables with the first and second dimensions of the factor map. The further a variable is away from the origin of the axis, the more it is correlated with the axis in question and allows better discrimination against the goat farmers. For example, variables related to breeding and feeding in the first axis (horizontal) and those related to using manure and having a vegetable garden in the second axis (vertical) are the most discriminating variables. The graph of the modalities of the variables (2b) shows the distribution of the modalities of the farming practices and their closeness among the goat farmers (represented by the distribution of the dashboard).

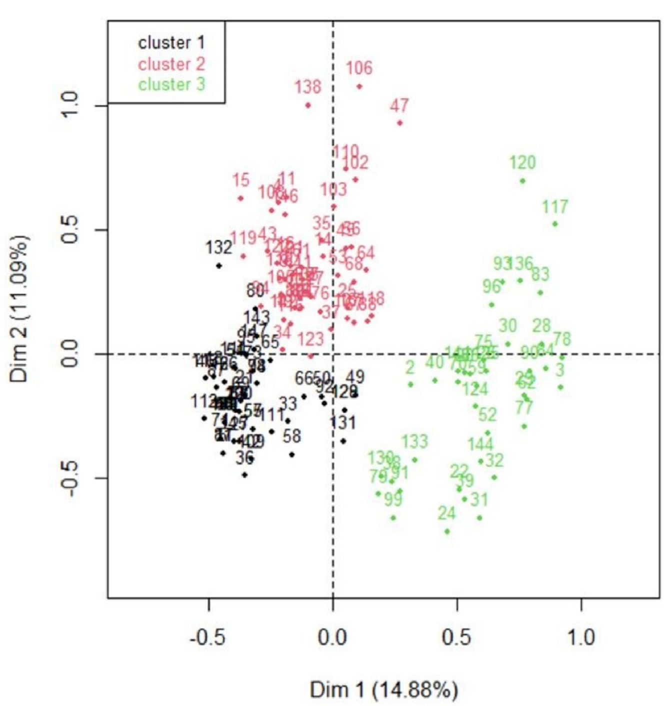

Fig. 3. Projection of the dendrogram of farmers on the factor map, distinguishing three groups of farmers: black points (1), red-(2) and green-(3).

important pillar of the sustainable intensification of agriculture (Latruffe et al., 2016; Grillot et al., 2018; Stark et al., 2018; Kuyah et al., 2021), the different agroecosystem components in rural areas in the western RDC should not be located at more than 2.5 km apart. A short distance allows the optimal management of the separated components through goat farmers' practices that link the crop and livestock components.

Agroecosystem fragmentation was probably due to the itinerant nature of traditional peasant agriculture. Extensive agriculture requires fertile land when it becomes less productive or is left fallow (Tang and Yap, 2020; Omasombo-Tshonda et al., 2012). The agroecosystem also becomes fragmented when farmers grow crops that do not have similar ecological or soil-quality requirements (Baker Capel, 2011; Mafwila et al., 2017). For example, cassava and maize require highly fertile and depleted soils, respectively (Cairns et al., 2013; Mahungu et al., 2014), whereas growing leguminous plants such as groundnuts and cowpeas, in fair or good conditions, can contribute to restoring soil fertility (Acevedo-Siaca Goldsmith, 2020; Kouadjo Paul et al., 2020). In contrast, in most farming communities in the western DRC, fragmentation makes it possible to isolate rangelands or pasturelands from croplands to avoid roaming livestock damaging crops.

Despite fragmentation, the remoteness of agroecosystem components and extensive crop and livestock farming, the findings revealed that at least half of the goat farmers acted positively to stimulate interactions between livestock and crop components. These farmers used crop residues as animal feed (53% collected them from their farms) and animal dung as soil fertiliser (50% collected it from their farms, and 52% sourced it from neighbouring farms). These farming practices are important aspects of the ecological intensification of agriculture (Stark et al., 2016, 2018; Syampunga et al., 2021) and are common in organic farming (Gamage et al., 2023). Similar farming practices that promote ecological

Table 3
Characterisation of the classes according to the discriminant variables of the classification.

Discriminating variable	Modality	% of all respondents	Cluster 1 % of the category	Cluster 1 V-test	Cluster 1 p value	Cluster 2 % of the category	Cluster 2 V-test	Cluster 2 p value	Cluster 3 % of the category	Cluster 3 V-test	Cluster 3 p value
Rearing mode	Roaming	72	95	5	< 0.001	100	6	< 0.001	3	-11	< 0.001
	Confined	14	5	-2.4	0.0162	0	-4	< 0.001	46	6	< 0.001
	Tethering	14	0	-4	< 0.001	0	-4	< 0.001	51	8	< 0.001
Free grazing	No	25	2	-5.5	< 0.001	0	-6	< 0.001	92	11	< 0.001
	Yes	75	98	5.5	< 0.001	100	6	< 0.001	8	-11	< 0.001
Feeding with crops residues	No	58	80	4.2	< 0.001	70	2	0.028	10	-7	< 0.001
	Yes	42	20	-4.2	< 0.001	30	-2	0.028	90	7	< 0.001
Feeding with forage in enclosure plot	No	77	95	4.1	< 0.001	89	3	0.009	36	-7	< 0.001
	Yes	23	5	-4.1	< 0.001	11	-3	0.009	64	7	< 0.001
Possessing vegetable gardening	No	42	89	9.2	< 0.001	2	-8	< 0.001			
	Yes	58	11	-9.2	< 0.001	98	8	< 0.001			
Using animal manure	No	49	96	9.5	< 0.001	9	-7	< 0.001			
	Yes	51	4	-9.5	< 0.001	91	7	< 0.001			

Legend: The V-test is the level of discrimination of a variable for a cluster.
Variables with a p value < 0.05 and a V-test ≥ 2 significantly characterise the cluster.

intensification have been implemented by smallholder farmers in Kinshasa Province (Mafwila et al., 2018), Burkina Faso (Vall et al., 2017), Madagascar (Vall et al., 2014) and Kenya (Musafiri et al., 2022). Using crop residues to feed goats and applying their manure as soil fertiliser promotes nutrient flows between livestock and cropland components, thereby contributing to ecological intensification within the agroecosystem. On the one hand, the smallholders limit the need for external inputs, and on the other hand, animal manure improves soil health in terms of their biodiversity (microorganism and microbial diversities), leading to nutrient cycling by soil litter decomposition and mineralisation, which is an important ecosystem service according to Struik and Kuyper (2017).

Several factors were positively associated with these goat farmers' practices, promoting ecological intensification between the crop and livestock components. The most significant factors were agricultural training, mixed livestock farming (pigs and goats), owning vegetable gardens, the proximity of livestock to cropland and keeping goats tethered or in a confined area. Agricultural training appears to have equipped goat farmers with agricultural skills, enabling and empowering them to use crop residues as animal feed and animal manure as soil fertiliser. Mafwila et al. (2017) also reported the importance of such training in Kinshasa Province, where the adoption of farming practices likely to lead to ecological intensification was mostly observed among trained smallholder farmers. Vall et al. (2014) and Ogisi and Begho (2023) highlighted the importance of capacity building through training or providing agricultural information to farmers in the SSAto support ecological intensification within agroecosystems. Besides agricultural skills, adding pigs to goat farming could have a positive influence on using manure as fertiliser since pig manure has a high fertilising value, as reported by Seydoux et al. (2008) and Menzi et al. (2016). Pig manure could especially be beneficial in vegetable gardening, which requires high nitrogen inputs (Neuweiler and Krauss, 2017).

In addition, as noticed by Landis (2017), ecosystem services are strongly influenced by the landscape design of the agroecosystem. In this regard, the proximity between the cropland and livestock plots (distance not exceeding 2.5 km) could positively influence ecological intensification because of the easier transportation of manure or crop residues. The use of manure allows a shortening of the fallow period and limits the risk of further agroecosystem fragmentation, a motivation to change practice in favour of ecological intensification.

A close proximity between croplands and livestock plots is advantageous, especially for goat breeders in urbanised areas, where goat herds are confined or tethered and fed mainly crop residues. Under such conditions, the goat's freedom to scavenge forage is reduced, especially when tethered, and animal welfare is compromised, according to the standards of the World Organisation for Animal Health (Garcia, 2017).

Regarding categorisation, smallholder farmers were clustered according to their farming practices, such as "rearing" and "feeding" methods, "type of crops" and "use of fertilisers", which explained 26% of the variability among goat breeders in the western part of the DRC. Sraïri et al. (2017) also observed these distinctive practices among oasis breeders in Morocco. Interestingly, Salas et al. (1988) revealed that, in the West Indies, farmer age could also influence the typology of stockbreeders, based on their breeding practices. In this study, however, age did not seem to be a significant factor influencing goat breeders' practices that promote ecological intensification between crop and livestock components.

The HAC distinguished three clusters of traditional goat breeders (Fig. 3). Each category was described with the discriminating characteristics presented in Table 3.

In the first cluster, goat farmers completely relied on the spontaneous productivity of different agroecosystem areas such as rangelands, fallow lands and croplands. Goats were allowed to range free, enabling them to forage for palatable fodder according to their selective behaviour (Lee et al., 2019; Dias-e-Silva Abdalla-Filho, 2020; Chebli et al., 2022). Such extensive goat farming in the western part of the DRC is similar to that reported by Boval et al. (2012) for the West Indies. Goat farmers in this cluster did not use livestock manure as soil fertiliser because they had neither vegetable gardens to valorise it nor crop residues to feed goats. Such farming practices could not promote, at the farm scale, nutrient cycling, which is a pillar of sustainable intensification, as noted by Ghaley et al. (2014), González-De-Molina and Guzmán Casado (2017), Struik and Kuyper (2017) and Kleijn et al. (2019).

However, having a vegetable garden helped initiate ecological intensification in this cluster because of the high value of goat manure for fertilising vegetable crops. As mentioned by Mafwila et al. (2017) and Vall et al. (2014), it would be better to provide goat farmers with agricultural training to strengthen ecological intensification and reduce their dependence on external inputs. Although the goat breeder practices in Cluster 1 do not reveal direct evidence of ecological intensification at the farm scale, such a situation could be different at the scale of an entire village or territory. At a larger scale (village or territory), the free-roaming goats return their manure, in one way or another, as soil fertiliser through excretion while moving and foraging on fallow land, rangelands and croplands. Thus, their excreta could be considered positive drivers of the nutrient flows in the agroecosystem components, although nitrogen is quickly lost from animal manure (Nasiru et al., 2014; Maltais-Landry et al., 2018; Chen et al., 2023). This issue deserves further investigation to understand the extent of the ecological services of free-roaming goats within a given agroecosystem.

The second cluster of goat farmers differs from the first in their use of goat manure as fertiliser in vegetable gardens. As vegetables require fertile, healthy soils, animal manure adds value to ecological intensification, and smallholder farmers do not have to rely on external inputs such as chemical fertilisers.

In the last cluster, farmers had total control over their goats by tying them with a rope or keeping them confined to an enclosed area. This cluster depended on the crop residues used as animal feed. Feeding animals crop residues created a strong link between the livestock and the cropland components, with regular nutrient cycling on both sides. Such farming systems are also widespread in Guadeloupe and several other African countries (Boval et al., 2017), where farmers must supply livestock with crop residues. This method could appear as a constraint to increasing the livestock population because of the additional labour required to collect crop residues and green fodder as well as to move tethered animals from one pasture to another and to monitor animal welfare. Thus, the goat farmers in this cluster must spend considerably more time working than those in the first and second clusters. Although such systems can be difficult to manage and require complex work, they offer some advantages. Besides the prevention of crop damage by limiting the roaming of goats, farmers in the third cluster can collect more goat manure (which is not possible when the animals are roaming freely) and use more crop residues as animal feed. The practices of the goat farmers in this cluster contribute to ecological intensification by limiting the use of external inputs.

The results of our research suggest that traditional farming systems should not be overlooked in favour of more conventional farming systems because the local knowledge and traditional practices of goat farmers can support the sustainable intensification of small-scale farming. The use of traditional knowledge and practices of smallholder farmers is therefore important as it not only reduces dependence on modern inputs but also minimises negative impacts on the environment. Considering the western part of the DRC, traditional practices and knowledge are limited to using animal manure as soil fertiliser and crop residues as animal feed. However, given the sociological and ecological particularities of each area in SSA, these traditional practices and knowledge could have a much wider range of applications beyond nutrient flow, for instance in animal health or weed control in cultivated fields. Thus, the different types of traditional goat farming, the local practices and knowledge and the potential interactions among various components of the agroecosystem at the farm and village level constitute the basis for intensifying traditional farming systems. Possible intensification models for traditional farming systems in different SSA areas could follow different schemes of intensification, depending on their specific sociological and environmental characteristics. It is therefore important to consider the specific characteristics of each region when developing models or policies for sustainable intensification of traditional farming systems. This provides novel opportunities for deep investigations.

5. Conclusion

Integrated crop and livestock systems deserve more attention in sustainable agriculture. Ecological intensification, as one of the pillars of the sustainable intensification of smallholder farming in SSA, could be achieved using the local knowledge of traditional goat farmers. In the western part of the DRC, among the five components of the agroecosystem identified at the farm and village scales, the natural savannah, animal husbandry and cropland components showed a huge potential for ecological intensification through traditional goat farming practices. At least half of the goat farmers acted positively to stimulate interactions between livestock and crop components, allowing them to be classified into three clusters. Farmers in the first cluster allow goats to roam freely, without animal care or the valorisation of manure or crop residues. This farming practice does not directly contribute to ecological intensification but has an indirect effect when the roaming goats freely gather fodder from the savannah, fallow land and even croplands, leading to the spread of their manure. The second cluster differs from the first in valorising goat manure to improve soil health, especially for vegetable gardening, thereby facilitating ecological intensification. The last cluster includes farmers who kept goats tethered or confined to enclosed areas, feeding them mainly with crop residues, and using animal manure on croplands. This allows a positive interaction between livestock and cropland components and contributes to ecological intensification in agroecosystems.

Several factors were associated with the farming practices seen among the goat farmers, including agricultural training, vegetable gardening, keeping goats tethered or in an enclosed area and the proximity between the croplands and the livestock.

The results reported here highlight the significance of supporting smallholder farmers through capacity building, which includes integrated livestock-cropland management strategies that build on local knowledge and farmers' practices to enhance ecological intensification within a given agroecosystem. To enable smallholder farmers to use their local knowledge to find the best management model attuned to available resources and limit their dependence on external inputs, training on sustainable intensification needs to be expanded. The traditional management strategies used by smallholder farmers, particularly those who promote nutrient flow among agroecosystem components, open up avenues for further research on the transfer of fertility from rangeland to fallow land or cropping land through goat herding.

Data availability

Data will be made available upon reasonable request.

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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