

Livestock roles in agroecological transitions in mixed crop-livestock systems of Tunisia

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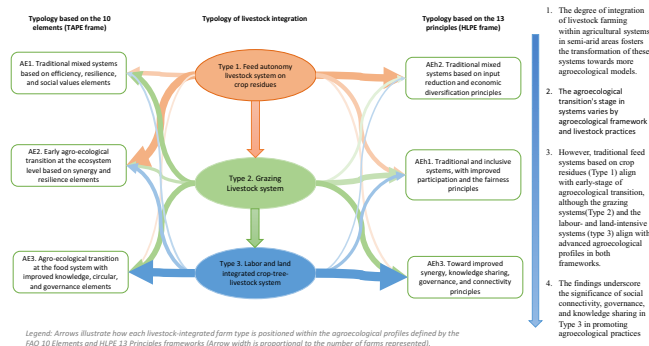
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HIGHLIGHTS

- Livestock drives agroecological transition in Kef-Siliana mixed systems.
- Livestock enhances mainly recycling, diversity, and synergy in Tunisian mixed systems.
- Agroecological transition in Tunisian mixed farming varies with the assessment framework and livestock management.
- Governance and weak social connectivity limit the resilience of the mixed agricultural systems.
- Knowledge sharing is key to scaling up agroecological transitions in farming systems in Tunisia.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Despite the well-recognized role of livestock in providing goods and ecosystem services, agronomy research over the past decades has predominantly focused on plots and crops, often underestimating the contribution of animals to economic diversification within mixed farming systems. While integrated livestock-crop practices remain among the most frequently cited examples of agroecology in action, few studies assess the extent to which livestock contribute to the agroecological transition, particularly in integrated crop-livestock systems. Most of them focus on the use or non-use of these practices, particularly in mixed livestock systems. **OBJECTIVE:** The objectives of this study are to 1) develop a method for characterizing the agroecological transition stage of crop-livestock farming systems and 2) analyze how integrating livestock into crop farming systems can promote agroecological transitions. The analysis compares farms at different stages of agroecological transition, assessed using indicators corresponding to FAO's ten elements and HLPE's thirteen principles of agroecology, across farms with contrasting levels of livestock integration.

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METHODS: This study used data collected from a survey administered to 692 households in northwest Tunisia. Factor and cluster analyses were used to analyze the data and identify defining characteristics of crop-livestock farms at different stages of agroecological transitions, and to distill the relative importance of livestock contributions to agroecological performance, in line with agroecological principles.

RESULTS AND CONCLUSION: The results show that livestock play a crucial role in the agroecological transitions of Tunisian mixed farming systems. Increasing livestock numbers on mixed farms is associated with enhanced synergies among crops, trees, and animals, particularly through nutrient recycling and the utilization of residues as livestock feed. However, challenges persist regarding knowledge co-creation, recycling and connectivity, and land and resource governance in landscapes with mixed farming systems.

SIGNIFICANCE: The study addresses the discrepancy between global frameworks and on-the-ground realities by integrating localized analyses of farming and livestock systems with broader principles of agroecology. While integrating livestock into farming systems in dryland areas can be considered a transformative pathway toward sustainable agriculture, the findings underscore the significance of social networks and connectivity between producers and consumers, governance, and knowledge sharing in promoting agroecological practices.

1. Introduction

Mixed farming systems, which combine crops, livestock, and/or aquaculture, are prevalent in developing countries and are gaining global interest as a climate change adaptation strategy (Baker et al., 2023). In the North African region, the mixed farming systems usually integrate crop (including tree) production and animal production at the farm level, using on-farm crops or crop residues as livestock feed and on-farm manure as crop fertilizer (See Photos 1). This system covers over 50% of cultivated land in North Africa (Ouessar et al., 2021). Most of these mixed systems are managed by smallholder family farms, coexisting with crop-oriented systems operated by medium and large holdings, as well as livestock-oriented systems found in pastoral and agropastoral areas (Marzin et al., 2016; Alary et al., 2019). In these mixed systems, livestock integration is generally presented as an agroecological practice (Requier-Desjardins et al., 2024) that enhances interactions and synergies between agricultural activities and rural landscapes. This, in turn, can lead to the optimization of agroecological properties within agroecosystems by improving nutrient cycles (Ryschawy et al., 2014; Vall et al., 2023) and biodiversity (Benoit et al., 2021; Steinmetz et al., 2021; Resare Sahlin et al., 2024). Besides, livestock also plays a multitude of roles in mixed crop-livestock systems, providing essential goods and services such as meat, milk, manure, and transportation (Herrero et al., 2013; Martin et al., 2016). Additionally, livestock can enhance the nutritional value of smallholder crops and effectively utilize crop and tree residues and stubble, contributing to resource optimization (Dumont et al., 2019; Van Zanten et al., 2019), through promising livestock feeding strategies (Röös et al., 2017; Genest-Richard et al., 2025) to reduce feed-food competition (Barbieri et al., 2022; Röös et al., 2021). Carefully managed livestock grazing systems can promote biodiversity on pastureland, for example, creating habitats for medicinal and aromatic plants and contributing to the aesthetic value of the landscape, attracting tourism and generating diverse income opportunities (as described by Davis (2005) in south Morocco or Beudou et al., 2017 in France and Alary et al., 2024). During periods of drought or flooding, livestock husbandry also represents a vital coping strategy for rural communities (Turner, 2002; Gautier et al., 2016; Alary and Frija, 2022). Furthermore, livestock plays a crucial role in rural societies due to its cultural significance. Therefore, recognizing the value of livestock is essential for ensuring the socioeconomic and environmental sustainability of rural communities. However, beyond these well-recognized roles of livestock, the plot- and crop-centered focus of agronomy research over the last decades has led to a neglect of research into livestock's multiple contributions at the farm or landscape level.



Photo 1. Mixed crop-livestock system on the Kef-Siliana transect of Tunisia (@Zied Idoudi, ICARDA, Tunisia).

Over the past decade, there has been a notable increase in interest in agroecology across research, political and social spheres. This interest is reflected in the work of numerous researchers, including Altieri et al. (2015), Wezel et al. (2020), De Molina et al. (2019), and Anderson et al. (2021). For Stark et al. (2018), the functioning of farms through crop-livestock integration practices remains a key determinant of the system's agroecological performance. To sustain efforts toward an agroecological transition or agri-food transformation, Ryschawy et al. (2017) emphasized the importance of using multi-level approaches to the agroecosystem, from the plot to the landscape levels. Gliessman and Ferguson (2020) further pointed out the need to integrate ecological and human considerations from the field to the meal. In an attempt to clarify what it means to transition to agroecology, the Food and Agriculture Organization (FAO) of the United Nations conducted a regional consultation process from 2017 to 2020, which enabled the identification and definition of 10 agroecological elements (FAO, 2018). In parallel, the High-Level Panel of Experts (HLPE) of the Committee on World Food Security (CFS) (<https://www.fao.org/cfs/cfs-hlpe/en>) proposed a list of 13 consolidated agroecological principles based on a literature review and online consultation (HLPE, 2019). These two frameworks for understanding agroecology transitions have been widely applied, including in household survey tools in multiple countries, like the Tool for Agroecology Performance Evaluation (TAPE) (Mottet et al., 2020) or the Holistic Localized Performance Assessment (HOLPA) for collecting evidence on the impact of agroecology (Jones et al., 2024).

However, each agroecological principle or element raises numerous challenges regarding its definition and interpretation, which evolve with research and socio-ecological perspectives (Wezel et al., 2020). At the agroecosystem level, the agroecological approach aims to enhance the benefits of biological interactions and synergies (as outlined by Gliessman, 1990 in HLPE, 2019), while concurrently reducing reliance on synthetic external inputs. It is anticipated to have a beneficial impact

on animal and soil health, as well as the socioeconomic viability of family farms, through reduced inputs and resulting economic diversification. By using local knowledge, especially on biodiversity (seed and breeds) and practices (such as resource management, intercropping, etc.), agroecological practices should align with the socio-political principles of food sovereignty, social justice, local identity, and indigenous rights (Altieri and Toledo, 2011) to accompany the food system transformation. Wezel et al. (2020) proposed a cross-reading of the two extended agroecological frames, i.e., the HLPE (2019) and FAO (2018), demonstrating both their complementarities and similarities. The authors identified the two primary prerequisites that inform the logic and then used the two frames. While the HLPE (2019) focuses on identifying principles that provide norms or causative statements for decision-making, the FAO (2018) developed a framework for local agroecological implementation statements or assessments.

Existing studies on agroecological transitions often consider the integration of livestock into mixed farming systems as an agroecological practice by itself. However, this perspective underestimates the wide gradient in how livestock is actually integrated. In reality, these varying forms of integration differ substantially, leading to contrasting contributions to key agroecological principles such as recycling, diversity, and system synergies (as described by Martin et al., 2016). Notably, the exchange of feed or manure between livestock and crop components is often recorded as a single agroecological practice. Ameer et al. (2020) recorded a dozen agroecological practices in Tunisia, among which the most frequently adopted were mixed integrated crop-livestock farming (100% of interviewed farmers adopting this system) and the use of organic manure (90% of interviewed farmers). There was no disaggregation of crop-livestock systems to understand variations in system design across farms. And, implementation of these practices can vary significantly across farms. For instance, the methods for managing manure stocking and spreading vary significantly and may not have the same impact on soil health or crop productivity. These limitations have created a knowledge gap on how to effectively design and manage crop-livestock systems to support agroecological transitions.

As the agroecological approach to achieving sustainable development of the food system gains prominence, recent publications have begun to consider livestock systems as a critical component of an agroecological transition (Wezel and Peeters, 2014; Dumont et al., 2013). System resilience has been shown to depend on animal health, which is closely linked to biodiversity and soil conditions (Wezel et al., 2020). Enhancing locally adapted breeds and maintaining soil health are also critical for sustaining plant diversity, productivity, and overall system stability. Both improved animal health and management contribute to system efficiency by reducing external inputs and promoting nutrient recycling. Beyond their biophysical roles, livestock strengthen social cohesion and facilitate resource sharing within rural communities (Alary and Frija, 2022). This suggests that livestock can serve as a catalyst for diversification and synergy within the agroecosystem, while also fostering resilience, social values, and governance within the food system, thereby intervening in the whole food system.

This study aims to evaluate the transformative role of integrating livestock into cropping systems in advancing agroecological transitions across the food system. Using data from farm-household surveys in Kef-Siliana, Tunisia, we: 1) develop a method for characterizing the agroecological transition stage of crop-livestock farming systems and 2) analyze how integrating livestock into crop farming systems can promote agroecological transitions in northwest Tunisia taking into account the two agroecological assessment frameworks widely recognized. Results show how crop-livestock integration, feed autonomy, soil fertility, and the social relationships surrounding livestock enhance system performance and sustainability, particularly through nutrient cycling, improved soil fertility, and increased agri-food system resilience, which are central to the agroecological transition. In addition, the study finds complementarities and convergences in livestock contributions to agroecological performance across the FAO's 10 elements (FAO, 2018) and

the HLPE's 13 principles (HLPE, 2019), highlighting the influence of methodological decisions.

2. The conceptual and analytical frame

The FAO's 10 Elements (FAO, 2018) and the HLPE's 13 Principles (HLPE, 2019) provide complementary frameworks for guiding and assessing agroecological transitions toward more sustainable food systems. Both frameworks emphasize key ecological processes, including recycling, biodiversity, soil and animal health, input reduction, diversification, and the promotion of synergies (Nicholls et al., 2016). They also recognize the importance of broader social dimensions such as equity, governance, collective knowledge, and market access. However, they differ in how these dimensions are structured and articulated. The FAO framework integrates several ecological and socio-economic processes into broader elements and highlights outcomes such as diversity, resilience, and circular and solidarity economies. In contrast, the HLPE framework presents a more explicit set of principles linking ecological, social, and governance dimensions across the entire food system. Fig. 1 summarizes the two frames and the articulation between the principles and elements we propose to integrate in assessing the livestock contribution to agroecology transformation pathways.

As illustrated in Fig. 1, the FAO framework emphasizes diversity, efficiency, recycling, and synergies at the agroecosystem level as the key drivers of agroecological transformation. Efficiency refers to practices that reduce dependence on external inputs while enhancing farm productivity and household wellbeing (Titttonell, 2014). The studied mixed crop-livestock systems include the use of organic matter instead of chemical fertilizers, reductions of external labor and veterinary costs, and improvements in household equipment and living conditions. The recycling contributes to efficiency through the reuse of locally available biomass, nutrients, seeds, water, and animal genetic resources, while traction animals represent the use of renewable energy within the system (Pretty et al., 2012; Gliessman, 2014). Diversity is reflected in the diversification of crops, livestock, and off-farm activities, providing both ecological and economic benefits and contributing to biodiversity (Darnhofer et al., 2010), while Synergies encompass interactions among crops, livestock, trees, soils, and grazing lands, thereby supporting ecosystem health (Titttonell, 2014; Altieri et al., 2015).

Knowledge sharing and co-creation facilitate the adoption of agroecological practices through social networks, participation in organizations, and access to expertise (Tengö et al., 2014). While the FAO (2018) framework highlights circular and solidarity economies, as well as responsible governance, the HLPE framework emphasizes connectivity, governance, participation, fairness, and social values. In this study, these dimensions are assessed through market integration, perceptions of governance and land security, the participation of women and youth, and food consumption practices.

Finally, resilience is considered as the capacity of farming systems to adapt to external shocks while maintaining their functions (as in Berkes and Folke, 1998; Folke et al., 2002). In the North African context, it is shaped by economic diversification, local solidarity mechanisms, and access to public support and services. Adapting the global agroecological frameworks to local mixed crop-livestock systems, therefore, required contextualizing several principles and indicators (Alary et al., 2022).

3. Materials and methods

3.1. Case studies

The Tunisian agroecological living landscape (ALL) in transect Kef-Siliana is located in the semi-arid zone of northwest Tunisia and was identified as a priority zone by national experts and decision-makers during the national inception workshop of the CGIAR research initiative on Transformative Agroecology (2022–2024). The zone was prioritized due to its diversification potential and the prevalence of mixed

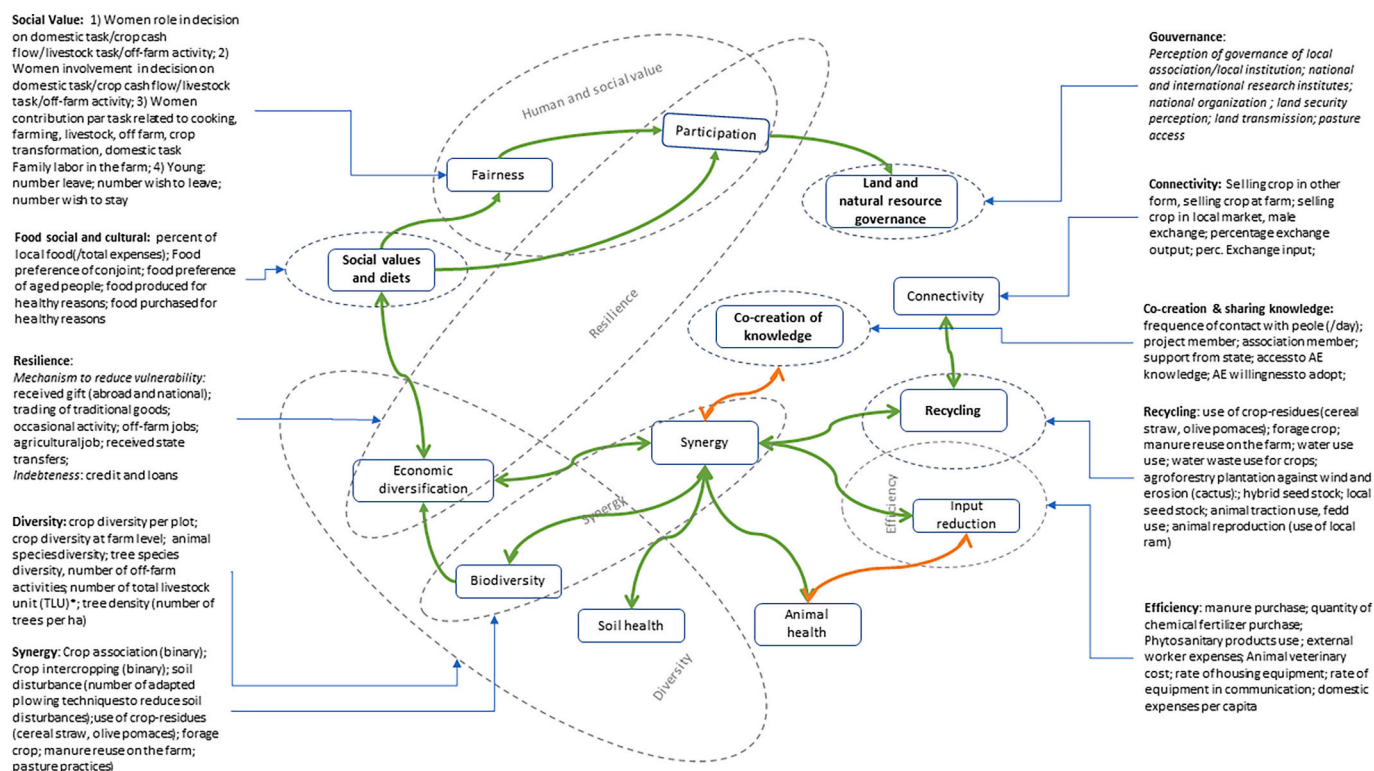


Fig. 1. Conceptual and methodological framework of agroecology: definitions and linkages across HLPE's 13 agroecology principles (rectangles with a blue border) and FAO's 10 agroecological elements (circles with a dashed border). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cereal-tree-small ruminants (sheep and goats) systems. The farming system that prevailed in this semi-arid zone had particularly low resilience to climate change, market volatility, and degradation and scarcity of inputs and resources. The targeted region is characterized by compact plot sizes that rarely exceed 5 ha, as outlined by Alary et al. (2022). So, the zone demonstrates a pragmatic approach to agricultural intensification, integrating livestock farming with annual crops, including arboriculture and, notably, olive cultivation.

In 2022, the living landscape consisted of four farmers' organizations

(FOs) (see localization in Fig. 2), which were selected along a gradient from South to North, spanning from mountainous to plain areas, and a gradient of partnerships (in terms of the number of years of partnerships with international and national research and development institutions working on sustainable agricultural transformation). The gradient of partnerships aimed to test how the degree of connectivity, participation, and governance built over the years may influence the AE transitions.

The transect Kef-Siliana is characterized by a continental climate, with cold, harsh winters and hot summers. The average annual rainfall

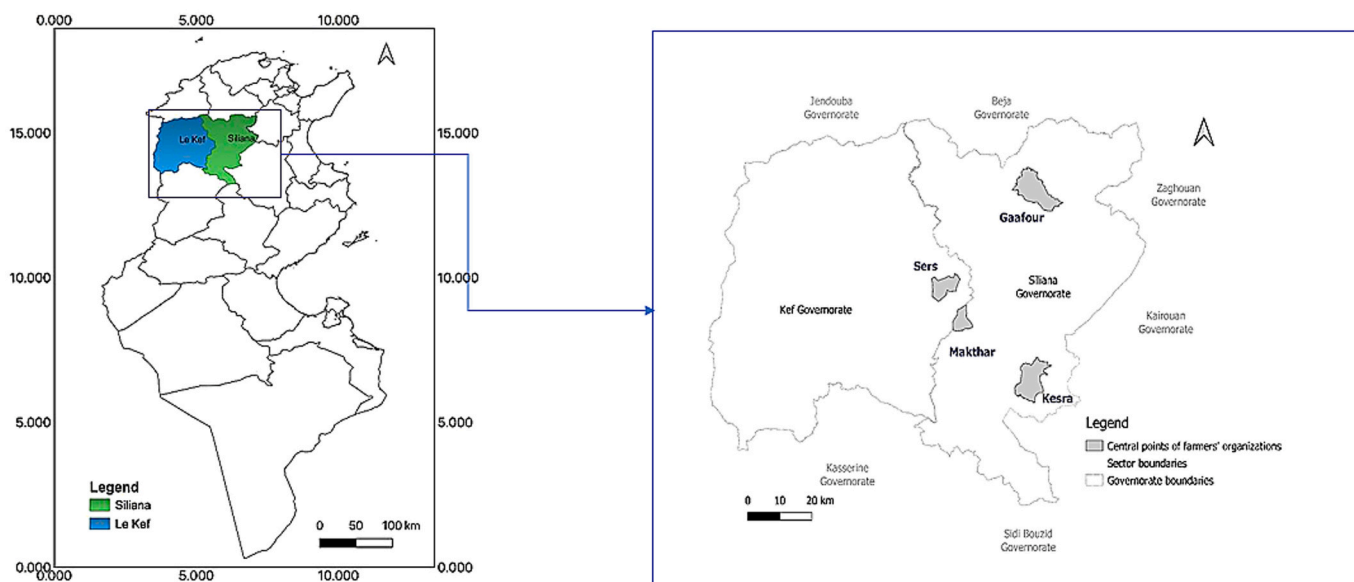


Fig. 2. Localization of the four localities composing the studied zone in Tunisia (ICARDA, 2022, in Alary et al., 2022).

ranges from 350 mm to 550 mm. According to the governmental studies (Atlas Kef, 2015; Siliana, 2013), these two governorates are classified as part of the bioclimatic semi-arid stage, which exhibits an increasing north-south gradient of aridity. The relief is rugged and compartmentalized with mountain ranges, high and medium plateaus, and alluvial plains. Different patterns and intensities of land degradation were observed across various zones in the ALL (Shiri et al., 2024; Shiri and Le, 2024).

The primary assets of farmers in both Kef and Siliana governorates are land and livestock. Around three-quarters of the total agricultural holdings are small-scale family farming systems, which utilize only 43% of the zone's total agricultural area (Marzin et al., 2016; Alary et al., 2022). In 2014, 66.8% of small family farms had an area of less than 5 ha, and 86.7% had an area of less than 10 ha. The predominance of cereal, trees, and small ruminant activities characterizes the farming system. Cereal cultivation, primarily for household consumption and partially sold to governmental agencies, is strongly dependent on climatic hazards, resulting in low, uncertain yields (averaging 14–16 q/ha). Arboriculture, focused on olive and fig trees, is practiced for both self-consumption and commercial purposes. We can also find other plant and tree varieties, such as almonds or apples for tree plantations, and Gramineae or leguminous species, such as vetch or Sulla. These two varieties have been developed in international projects over the past five years, especially in Chouania, Sers, and, recently, in Rahla. The Kesra zone was a new site, with a recent partnership.

The farming systems in question include a wide range of livestock, primarily ruminants such as cows for dairy production in zones with irrigation facilities and sheep and goats in less favorable zones, with sheep being primarily raised for meat and goats for milk and meat. Manure is also collected and used on agricultural lands, except in pastureland. Additionally, most farms raise poultry to meet the family's needs for eggs and meat. Other activities, such as beekeeping, are developing in the zone and constitute a non-negligible source of income.

3.2. Household questionnaire and survey

A farm household survey was implemented in 2022 as a baseline for the Agroecology Initiative. The primary objective was to conduct an initial assessment of the efficiency, resilience, and viability of household farming systems in the study area. A semi-structured questionnaire was conceived in modules, as presented in Table 1.

The target population comprises agricultural holdings that engage in at least one agrarian activity (cultivation, arboriculture, or animal husbandry) within the study area, with a preference for small- and medium-sized holdings of less than 20 ha (at least 90% of the sample). The sampling approach was built on one of the hypotheses of the Agroecology Initiative, namely that it be representative of 1) farms already showing signs of changing away from high-external-input and/or simplified practices and/or low-input and low productivity toward high-natural-inputs, diversified practices, and minimal waste. Farms were identified in consultation with extension services, farmer associations, and other local and national experts, and 2) Farms not showing any signs of changing away from high-external input or simplified practices, or even low-input and low productivity toward high-natural inputs, diversified practices, and minimal waste. The target proportion of selected farms was intended to be around 80% for those already exhibiting some signs of change and 20% for those not showing any signs of change. Within the living landscape in Tunisia, we assume that the “Farms already showing some signs of changing toward agroecological transformation” population comprises beneficiaries of farm organizations (FO) in the selected localities who have already participated in training or adopted socio- or technical innovations promoted in the area. By deduction, the population of “Farms not showing any signs of changing” includes the rural households in each locality who have not benefited from the activities developed in the FOs. The sub-population should be evenly distributed across the four localities (about 150

Table 1

Description of the semi-structured questionnaire used in the farm household (list of variables and scores are described in the SM1).

Modules	Themes	Farming system approach	Targeted AE principles
Module A	Household Identification and localization		
Module B	Family structure, occupation, and time allocation per activity	Family and human (age, education, family number, main occupations); youth migration	Economic diversification
Module C	Characteristics of the main house		
Module D	Household physical assets: farm and housing equipment	Rate of equipment per farm activity and domestic purpose	Efficiency
Module E	Own lands per farm household and pastureland access	Land asset	Diversity
Module F	Crop varieties and management per plot	Crop management practices; input use	Synergy; diversity; efficiency
Module G	Animal production and marketing per animal species	Livestock assets and animal transactions	Diversity
Module H	Breeding practices per ruminant species	Reproduction practice	Recycling
Module I	Feeding systems per feed source	Source of feed and use of crop residues	Recycling; efficiency
Module J	Awareness at the level of agroecological practices	How and by whom is the adoption of technologies decided?	Co-creation; knowledge sharing
Module K	Perception of technologies and willingness to adopt	Willingness to adopt	Co-creation; knowledge sharing
Module L	Social network	Daily contacts at the community level; member of a project or association; support received from a governmental organization	Co-creation; knowledge sharing
Module M	Other sources of income and transfers	Others activities	Resilience
Module N	Non-food domestic expenses		Efficiency
Module O	Access to socioeconomic infrastructure per social and economic infrastructure		
Module P	Shocks experienced by the household farm	Role of livestock in managing risks and shocks	
Module Q	Daily food ration		Social and cultural values
Module R	Access to credit, decision-makers, and use of borrowed money per source of credit	Access to credits and loans	Resilience
Module S	Decision-making and work involvement (by gender) per farm and domestic tasks	Women's involvement in decision-making and task management	Social value of fairness and participation (inclusion)
module T	Dietary influencers	Food processed and purchased for health reasons	Social and cultural values

households per locality). The first sample of 592 farm households was enlarged by 100 new farm households outside the influence of any FO and thus represents the control sub-sample (Shiri et al., 2024). Table 1 provides an overview of the semi-structured questionnaire developed for the household survey.

In total, 24 enumerators from the study zone were trained, along

with an additional team of four supervisors (one per locality). The questionnaire was translated into Arabic (using the Tunisian dialect) and developed on the SurveyMonkey platform, now known as Survey-ToGo. The enumerators were equipped with tablets to conduct the survey. The first survey round was conducted from January 14 to February 15, 2023, and the second from May to June 2023.

3.3. Methodological approach

Based on the conceptual framework of agroecology in part 3.1, the *first step* was to establish and compile a list of proxy variables or indicators for each AE principle, as defined in Fig. 1. Some variables can contribute to more than one principle. For instance, utilizing crop residues is part of recycling practices, which positively impact synergy (enhancing crop-livestock integration) and efficiency (reducing external inputs). Manure use at the farm level reduces external input purchases (and increases the system's efficiency) and positively affects soil health through ecological interactions (part of the synergy principle). The proxy indicators have been selected based on the methodological frame presented in Fig. 1, as well as on a review of the current state of agroecological principles in the studied area, Kef-Siliana (Alary et al., 2022c), resulting from a literature review and stakeholders' consultation. The proxy variables are grouped according to the principles or elements with which they interact, to maintain coherence within each.

Once the variables are selected for each AE principle, the *second step* is to assign a score to each factor based on its intensity. To illustrate, in terms of use of chemical fertilizer, the score decreases when the expenses related to chemical fertilizer increase per ha. Conversely, the score for crop residues increases with the quantity. Therefore, the scores were determined using a histogram score, which provides a method for measuring the distribution of data within a set. For each significant rupture, we consider a new score. The variable scores are presented in the supplemental material (SM1). There is no additional weighing system; i.e., all proxies for principles' indicators are treated as equally. The score for each principle (HLPE framework) or element (FAO TAPE framework) is calculated as a relative index at the individual level. First, the variables or parameters that compose each principle are scored and summed to obtain an aggregate score for each individual farm. This aggregated score is then normalized by dividing it by the maximum observed aggregated score across all individuals in the population. The resulting index therefore expresses each individual's performance relative to the best-performing case in the sample, making the assessment inherently population-specific rather than based on an absolute standard.

In the *third step*, we analyze the diversity of livestock integration level at the farm household level. We based this analysis on a set of variables related to the contribution of livestock in terms of physical assets, feed autonomy due to the use of local products at the farm and landscape level, the nutrient contribution of animals at the farm level, and the social value of livestock related to employment, social network, and food contribution (Table 2a). This analysis is based on a Multiple Factorial Analysis (MFA) and clustering analysis using the Ward approach (Ward Jr, 1963). All factorial and clustering analyses were performed using the XLSTAT software (version 2024.4.0). A similar approach, i.e., Multiple Factorial Analysis (MFA) followed by a Hierarchical Clustering analysis (HCA) was implemented to analyze the diversity of farm systems by using the main variables that reflect the structure of the farms, namely family composition and labor, land and livestock capital, and the crop system in place (see Table 2b).

In the *fourth and final step*, based on the relative index estimated for each AE principle or element, we conducted a Principal Component Analysis (PCA) to understand and explain interactions among AE principles and elements in the integrated crop-livestock systems, as determined by both the livestock integration typology and the farming systems' typology. A clustering analysis of the first factors of the MFA, which capture the most significant differences between modes of

Table 2

List of variables related to livestock integration and contribution (a) and the characterization of the family farm system (b) (legend: DT Tunisian Dinar; FTE Full Time Employment).

Themes	Variables	Range
a) Themes and Variables related to livestock integration and contribution		
Livestock and land (Physical asset)	TLU/ha	Continuous
	Livestock equipment (in % of total equipment)	Continuous
	Livestock asset (in % of total physical asset)	Continuous
Feed autonomy	Feed autonomy (number of months/year)	1–12
	Feed autonomy for Sheep and goats in barley grain purchase (months)	Continuous
	Feed autonomy for Sheep and goats in bran purchase (months)	Continuous
	Feed grazing collective (months of grazing)	1–12
	Feed grazing private pasture (months of grazing)	1–12
Animal contribution to the farm system	Use animal transport and traction	Yes/no
	Barley area (ha)	Continuous
	Oat area (ha)	Continuous
	Vetch area (ha)	Continuous
	Cactus (ha)	Continuous
	Nitrogen supply from manure (in % of total supply)	Continuous
	Nitrogen supply from on-farm manure (in % of total manure use)	Continuous
Labor	Time allocated to livestock (/total family FTE)	Continuous
	Time allocated by women to livestock (/total women FTE)	Continuous
Family dependence on animal foods	Meat and milk expenses/total HH expenses in DT	% Of total HH expenses in DT
Animal contribution to the social network	Network around livestock (number of contacts/total contacts)	% Of the total contacts (number)
	Access to the project	Yes/no
Animal contribution to family resilience in the face of shocks	Credit for livestock (/total credit in DT)	
	Sale of animals in case of shocks	Yes/no
	Use of animals in case of shock	Yes/no
	Animals affected in the case of shocks	Yes/no
b) Themes and variables used for the characterization of the family farm system		
Family structure and capital	Household size	Count
	Women adults in the household	Count
	Men adult	Count
	Marital Status of the household head	Discrete
	Educational years of the household head	Continuous
	Family full-time employment (FTE) in the farm	Continuous
	Owned land (ha)	
Land capital & cropping system	Number of land parcels	Count
	Wheat (ha)	Continuous
	Barley (ha)	Continuous
	Oat (ha)	Continuous
	Olive (ha)	Continuous
	Legume (ha)	Continuous
	Sheep	Count
Livestock	Goats	count
	cattle	count
Physical capital	Material equipment (in DT)	DT
	Land capital (DT)	DT
	Livestock capital (DT)	DT

integration and interaction, allowed us to establish a typology of farm households along an agroecological gradient, based respectively on the 13 principles (HLPE, 2019) or the 10 elements (FAO, 2018). The clustering analysis was developed using the hierarchical classification analysis (HCA) with the Ward method (Ward Jr, 1963).

4. Results

4.1. Analysis of the diversity of the farming systems in the living landscape

On average, farms had 1.66 TLU (Tropical Livestock Unit, equivalent to 250 kg liveweight; see Wilson, 1986), corresponding to approximately 16.7 heads of sheep and/or goats (median seven animals) or one head of cattle. These farms were integrated with two to three crop species, mainly dry cereals such as wheat (0.7 ha on average) and barley (1.28 ha), along with olive trees (0.38 ha on average), over an average agricultural area of 3.17 ha (median 1.5 ha). The household averages 3.5 members, with 1.9 adults (median of 3 persons and 2 adults).

The first PCA, based on the 19 variables characterizing farm and household characteristics (see Table 2b), revealed that 33.6% of the variability in farm diversity (measured as the total variance in the dataset) can be explained by household size and family labor engaged in agricultural activities. Larger households and those with more family labor use were associated with higher on-farm diversity (notably the integration of sheep, goats, and cattle). The larger households own, on average, around 15 ha of land, distributed across four separate plots, thus allowing for the diversity of biotopes and crops.

The initial PCA distinguished the diversity of family farms based on the structural components that define a farm, this includes: 1) the household size and the family labor engaged in the agricultural activities; 2) the land access and cropping systems by differentiating food and feed annual crops and the perennial crops like olive trees and 3) the animal stock related to bovine, sheep and goats (using variables in Table 2b). A fourth set of variables reflects equipment used for crop or livestock activities. The set of structural factors accounts for 33.6% of the variability differentiating the population according to the physical capital, mainly land, livestock, and equipment (each variable with a contribution of more than 11% on F1), and the family size and structure and their contribution to farm activity (Family size and composition variables contributing to more than 19% on F2). The third and fourth components of the PCA provided additional information about the variables of cattle and the family head's education level. The hierarchical cluster analysis (HCA) identified four farm types, each with similar levels of farm diversity, differentiated mainly by farm size, number of trees, household size, and livestock species (see Fig. 3). The first factor distinguishes the small farms (FS1 and FS3), with around [1.4–2.2] ha of owned land and [8–16] heads of sheep and goats, from the large-scale farm (FS4), with an average of 17 ha and 85 heads of sheep and goats. In between, we find the medium farm (FS2) with around 40 heads of sheep and goats and 7.7 ha of owned land. The second factor differentiates the two small farms (FS1 and FS3) according to household size and family labor. If FS1 accounts for approximately three family members with one full-time member working on the farm, FS2 accounts for double that. It is also important to note that FS1 primarily engages in crop and tree activities, whereas FS2 diversifies its

livestock activities by raising sheep, goats, and cattle.

In parallel, we implemented a second PCA using the 24 variables describing livestock integration (presented in Table 2a). The first two factors, representing 24.2% of the variability, reflect crop-livestock integration through manure management and livestock charges, as well as family labor engaged in livestock activities. Following the same approach described above, the HCA allowed differentiating three livestock system types (LS), i.e., the extensive feed system based on crop residues (LS1) or the grazing pastureland (FS2) on the first axis and the labor and land-intensive livestock system on the second axis (see Fig. 4).

Table 3 presents the geographical distribution (by locality) of the identified farm and livestock systems. The integration of livestock is widely influenced by the characteristics of the dominant farming systems embedded in each locality. For example, the extensive crop-residue-based feed system is dominant in the Kesra commune due to the extensive development of agroforestry, which utilizes fig and olive residues in the mountainous areas. However, with 3.4 ha of private pastureland, compared to 1.3–1.7 ha in the other localities, the Sers commune is mainly oriented toward a livestock-grazing system. Conversely, the Chouarnia community, which has an average of 4.2 ha of owned land (compared to 3.2 ha for the entire population), seeks to intensify its feed system. Due to their locations, the Kesra and Sers communes are most oriented toward tree activities, with centennial plantations of figs in Kesra and olives in Sers. The majority of medium- and large-scale mixed crop-livestock farms are located in Chouarnia.

Table 4 shows that the majority of farmers in the labor and land-intensive livestock systems (LS3) are beneficiaries of the farmers' associations (AD2. *Adherent and beneficiary* and AD3. *Beneficiary only* in Table 4) (almost 88% of the LS3), compared to 53–55% for more extensive feed systems.

4.2. Farm diversity and agroecological gradient based on the FAO 10 elements

Fig. 5 illustrates the agroecological gradient between each system, based on farm structure, livestock integration, location, and the degree of involvement in farmers' associations. Firstly, it is observed that along the Kef-Siliana transect, farms demonstrate comparable performance in terms of efficiency, resilience, and social values, irrespective of physical capital (typology FS) or livestock integration (typology LS). The most significant contrasts between systems are observed for the diversity and knowledge-sharing proxies, and to a lesser extent, for circular economy, recycling, local food, and governance. Within this framework, the most agroecological types are labor- and land-intensive livestock systems in large mixed crop-livestock farm systems, which are found in the Sers and Rahla communes. Most of these farms benefited from technological packages for crop and land improvement, which included a mix of forage seeds, among other items. Then, the following systems are the medium farms based on the grazing systems predominant in Kesra. There are fewer agroecological farms in Chouarnia, with the majority of farms outside the farm organizations and less aware of or interested in agroecological practices.

Using principal component analysis (PCA) on the ten elements of agroecology as defined in Part 2, followed by hierarchical classification (HCA), the farm population can be differentiated into three profile

Table 3
Geographical repartition of the livestock systems (LS) and farm system (FS).

	LS1. Extensive feed system based on crop residues LS	LS2. Grazing LS	LS3. Labor & land intensive LS	FS1. Tree-oriented FS	FS2. Medium mixed FS	FS3. Small mixed FS	FS4. Large mixed FS
Chouarnia	9%	22%	64%	15%	35%	21%	35%
Kesra	47%	17%	5%	29%	19%	22%	19%
Rahla	25%	20%	23%	25%	19%	18%	12%
Sers	19%	41%	9%	31%	27%	39%	35%
All sample	219	426	44	408	110	145	26



Fig. 3. Typological representation of the farming systems on the first two factorial axes (F1 and F2) (sample: 692 household farms).

groups based on agroecological status (Table 5). The first group (AE1) registered the highest score for social values, including women's and youth participation in decision-making and resilience, notably in food and service exchanges, which contrasts with the third group (AE3) (on the first axis of differentiation). The group AE3 records the highest scores for diversity, synergy, recycling, knowledge, circularity, and governance, confirming the most advanced stage in the AE transition. The group (AE2) has intermediate scores for AE transition at the ecosystem level (diversity, synergy, recycling, and circularity). By projecting the groups of livestock integration onto the factorial plan (Fig. 6), we can see that the most advanced farm systems, in terms of agroecology principles at the ecosystem level, are the land- and labor-intensive livestock systems, i.e., those with the most developed integrated crop systems for food and feed purposes. The extensive livestock systems are grouped in the second category (AE2) and are well-positioned with respect to the agroecological principles of social values.

4.3. Crossed analysis of livestock contribution to agroecology regarding the two AE frames (FAO's 10 elements and HLPE's 13 principles)

A second PCA was applied to the 13 principles defined in the HLPE frame for each farm, followed by a clustering analysis that identified three profiles of agroecological farm systems along the Kef-Siliana transect, presented in Table 6. The coefficient is the sum of the variable scores in each principle divided by the maximum achieved in the studied population. While the three agroecological profiles of farm systems concerning the 13 principles proposed in the HLPE frame

(HLPE, 2019) have relatively high levels of achievement for the principles of participation, input reduction and economic diversification, we can note significant differences regarding the principle of fairness (with the highest score for the traditional system, AEh1) and synergy (with the higher score for the systems using improved agroecological practices, AEh3).

Fig. 7 shows the population projection along the first two axes of the ACP, based on the agroecological profiles within the HLPE frame. We have also projected the agroecological profiles issued from the FAO's 10-element frame and the farm and livestock management typologies in supplemental variables to analyze the proximity between the two agroecological frames. The objective was to understand and analyze the links between agroecological profiles related to the FAO's 10 elements (FAO, 2018) or HLPE's 13 principles (HLPE, 2019), with the profiles of farming systems and livestock integration. We can easily see the proximity between the agroecological profiles from the two approaches, notably between the improved AE system toward bio- and social values and the advanced agroecological system (AE3). We also note that the most advanced agroecology systems are medium- to large-scale farms with advanced agroecological knowledge and practices in the studied zone. The most traditional systems, with little social and economic connectivity (close to AE1 in the FAO 10 elements approach), are mainly located in the mountainous Kesra community. The traditional and inclusive systems (AEh1) (close to the earlier AE system in the FAO's 10-element typology) correspond to the Sers community, which has witnessed the development and increasing dynamism of farm organizations for women.

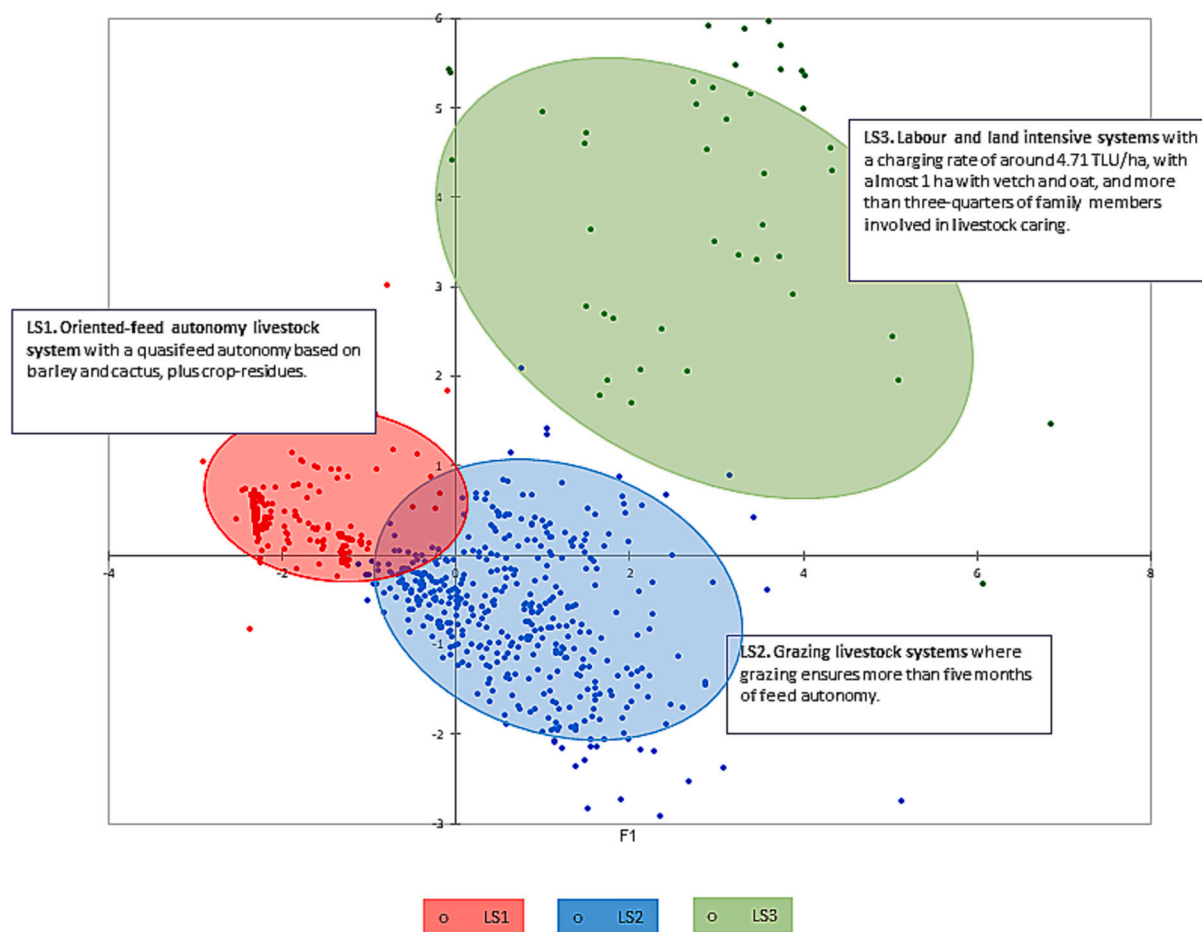


Fig. 4. Typological representation of the livestock farming systems (LS) on the first two factorial axes (F1 and F2) (sample: 692 household farms).

Table 4

Social repartition of the livestock systems (LS) and farm system (FS) according to their status vis-à-vis the farmers' associations.

	LS1. Extensive feed system based on crop residues LS	LS2. Grazing LS	LS3. Labor & land intensive LS	FS1. Tree-oriented FS	FS2. Medium mixed FS	FS3. Small mixed FS	FS4. Large mixed FS
AD0. No	43%	41%	11%	42%	32%	42%	23%
AD1. Adherent only	4%	4%	0%	4%	2%	3%	4%
AD2. Adherent and beneficiary	20%	28%	27%	19%	35%	31%	38%
AD3. Beneficiary only	33%	27%	61%	34%	31%	23%	35%
	219	426	44	408	110	145	26

As shown in Fig. 8, the percentage of livestock integration systems is shown for each identified agroecological profile. These profiles are categorized according to the 10 elements in the FAO frame (FAO, 2018) and the 13 principles of the HLPE frame (HLPE, 2019). We can see that extensive or traditional feed systems based on crop residues (LS1) or grazing (LS2) align with early-stage or traditional AE practices, although labor- and land-intensive systems (LS3) align with advanced agroecological profiles in both frameworks. However, Fig. 7 underscores the nuanced roles livestock systems play across different stages of the agroecological transition. According to the FAO frame, the grazing system (LS2) is classified as either a traditional or an advanced AE system. However, it is regarded as an improved AE system, linked to knowledge sharing, governance, and connectivity, based on the HLPE framework. So, the way adherence to agroecology components influences the performance assessment of a gradient of agroecologization. We can see that type 3, representing labor- and land-intensive livestock systems, is well represented in both frames as the most advanced AE systems,

highlighting the prominence given to agronomic and economic performance. In between, we find feed autonomy livestock systems (Type 1), which are considered to be at the very early stage in the HLPE frame and the transitional stage in the FAO frame.

5. Discussion

5.1. Main findings on the livestock contribution to the agroecological transformation

The analysis of the diversity of farming systems in the studied living landscape of the Kef-Siliana transect highlights significant heterogeneity among family farms, particularly in physical assets and in the degree of crop-livestock integration. The first Multiple Factorial Analysis (MFA) distinguishes farming systems based on structural variables such as land ownership, livestock assets, and cropping patterns. Four distinct farm types were identified, ranging from small-scale farms with limited land

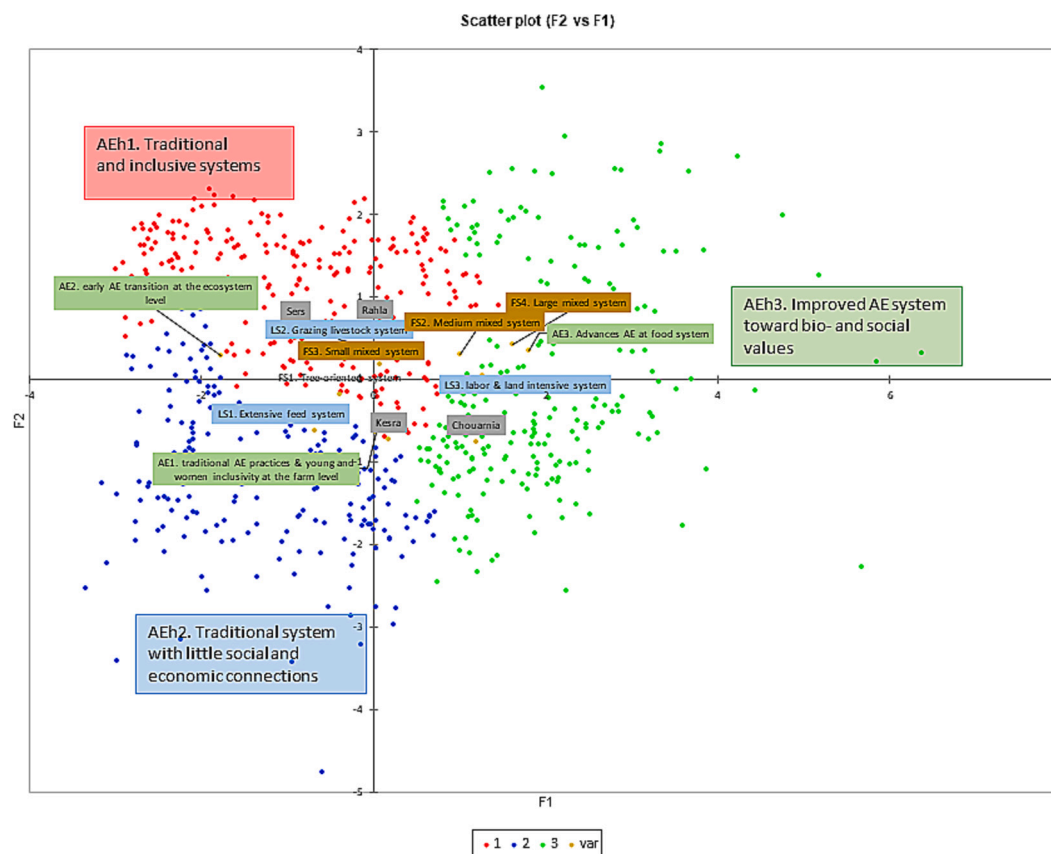


Fig. 5. Agroecological profiles of farms based on the FAO 10-elements frame (FAO, 2018) to compare a) livestock systems, b) farming systems, c) communities, and d) agricultural network.

Table 5

Profiles of agroecological status using a clustering analysis along the transect Kef-Siliana (Tunisia) (mean of the relative index for the 10 elements in the TAPE approach).

FAO's 10-elements	AE1. Traditional AE practices based on social values	AE2. Early AE transition at the ecosystem level	AE3. AE transition along the food system	All sample (Average)
Diversity	0.373	0.400	0.594	0.454
Synergy	0.347	0.682	0.738	0.587
Efficiency	0.799	0.779	0.764	0.781
Recycling	0.034	0.353	0.425	0.268
Resilience	0.850	0.811	0.840	0.834
Local food	0.144	0.305	0.319	0.255
Knowledge	0.152	0.174	0.418	0.246
Social value	0.629	0.473	0.562	0.555
Circular	0.076	0.142	0.265	0.160
Governance	0.142	0.099	0.274	0.171

and livestock (FS1 and FS3) to medium to large mixed farms with substantial land and diversified livestock activities (FS2 and FS4). A key insight is the influence of land access and labor availability in shaping the farm system and its functioning. This farm system differentiation is relatively common in the rainfed zones of the North African countries (Nordblom et al., 1995; Alary et al., 2019, 2022).

The second MFA reveals variations in livestock integration, identifying three livestock system types: extensive systems based on intensive use of crop residues (LS1), grazing-based systems (LS2), and labor- and land-intensive systems (LS3). These types reflect different strategies for managing feed resources and integrating livestock into crop production. The geographical distribution of these systems highlights the importance of local context: Kerira is dominated by crop-residue-based systems

due to its agroforestry practices, while Sers leans toward grazing systems because of the availability of private pastureland. These findings suggest that geographical and ecological factors heavily influence livestock integration and its contribution to farming systems, emphasizing the need for localized strategies in agroecological transitions (Hazell and Wood, 2008; Jeanneret et al., 2021).

The analysis also highlights the interplay between social factors and the identified farming systems. Labor- and land-intensive livestock systems (LS3) are closely associated with farmers who are active participants in farmers' associations, highlighting the role of social networks and organizational support in favoring the adoption of agroecological practices (or attributes) in these farms. Extensive feed systems (LS1) and grazing systems (LS2) are more prevalent among farmers with limited support from social or economic organizations, suggesting a potential gap in access to resources and capacity-building. These results emphasize the importance of fostering social connectivity and institutional engagement to enhance the adoption of advanced agroecological practices across diverse farming systems (Ferguson et al., 2019; Polge and Pagès, 2022; Blesh et al., 2023).

As already shown in the literature (Francis et al., 2003; Altieri et al., 2015; Dumont et al., 2013; Wezel et al., 2020, and also Stark et al., 2018), we demonstrate that livestock plays a pivotal role in agroecological transformation, particularly within mixed farming systems that integrate tree, crop, and livestock activities in North African countries. Integrating farm activities, which are widespread across the semi-arid regions of North Africa, improves synergies between the agricultural system's components. Through integration and synergy, livestock contribute to the sustainability of smallholder farms, particularly by utilizing crop and tree residues and promoting nutrient recycling (Ryschawy et al., 2014; Vall et al., 2023). Additionally, well-managed grazing practices can enhance biodiversity, support habitats for

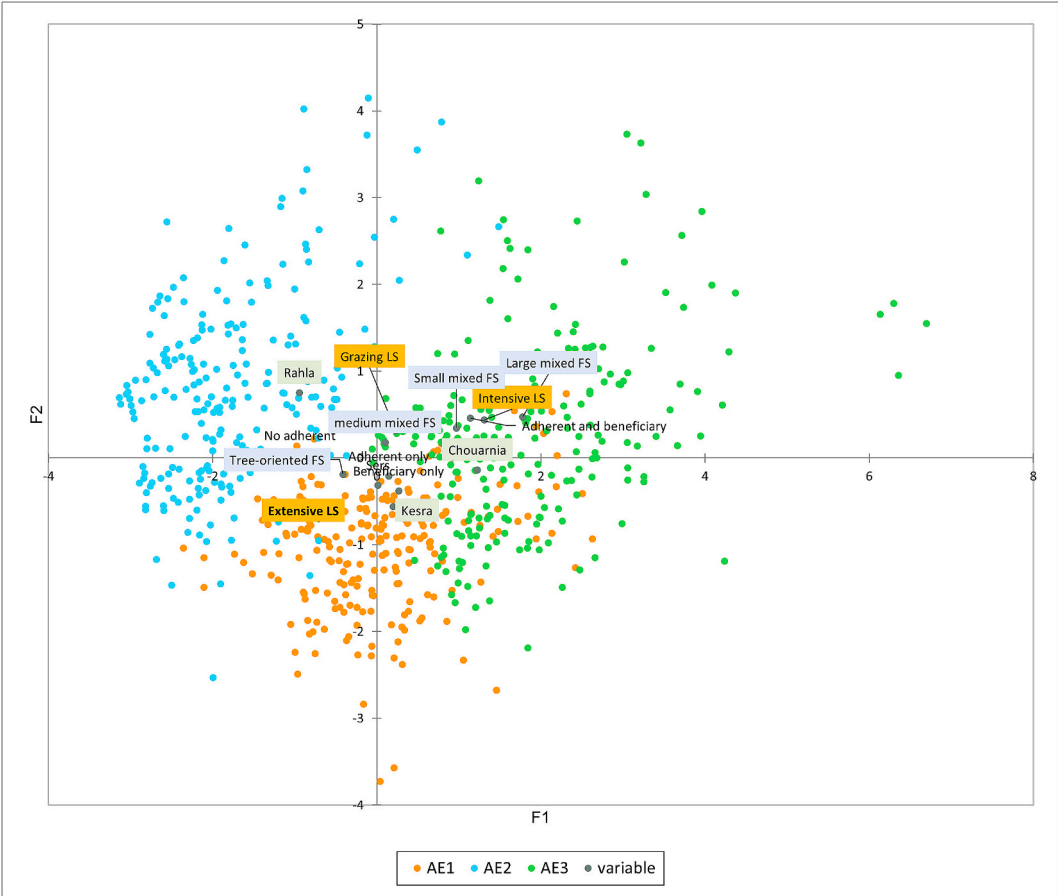


Fig. 6. Representation of the agroecological farm profiles on the first two factorial axes (F1 and F2) based on the FAO's 10 elements of the agroecological frame (sample: 692 household farms).

Table 6
Description of the three AE profiles about the 13 principles of agroecology as defined in [HLPE \(2019\)](#) (mean of the relative index for the 13 elements in the TAPE approach).

Valeurs	AEh1. Traditional and inclusive systems	AEh2. Traditional system with few social and economic connections	AEh3. Improved AE system toward bio- and social values	Av. Sample
Participation	0.92	0.71	0.80	0.82
Input reduction	0.78	0.80	0.77	0.78
Economic diversification	0.70	0.62	0.72	0.68
Biodiversity	0.47	0.44	0.57	0.49
Fairness	0.76	0.30	0.38	0.49
Synergy	0.33	0.25	0.70	0.43
Social values & diet	0.40	0.38	0.45	0.41
Recycling	0.20	0.16	0.43	0.27
Knowledge	0.14	0.15	0.44	0.25
Connectivity	0.12	0.10	0.32	0.18
Governance	0.15	0.09	0.26	0.17

medicinal and aromatic plants, as observed also by [Steinmetz et al. \(2021\)](#) or Resare Salhin et al. [Alary et al. \(2024\)](#). Especially in the mountainous zones of the Kef-Siliana transect, this function of grazing adds aesthetic and economic value through eco-tourism (as shown in Kesra), even if this activity is still underdeveloped in the countryside. So, the integration is a key driver to ensuring the ecological interactions and long-term viability of the agroecosystem, as already demonstrated by [Martin et al. \(2018\)](#). It also incorporates cultural and socioeconomic factors that are vital, as observed in many other countries and regions ([Alary et al., 2024](#)). Thus, mixed crop-tree-livestock systems in the semi-arid zones of the Kef-Siliana transect are inherently linked to the

agroecological principles of resilience, efficiency, social value, and synergy. We have identified gaps and weaknesses in agroecological principles within the local food system. This includes gaps in considering and stimulating the circular economy and governance at the local and regional levels in landscapes dominated by livestock presence and activities. We also found that the agroecological principle of knowledge sharing is particularly important for medium- to large-scale farms (LS3). It could serve as a key lever to facilitate the dissemination and adoption of agroecological practices in more traditional, less integrated livestock systems, particularly forage-self-sufficient systems (LS1) and pasture-based systems (LS2). Furthermore, the inclusion of women and young

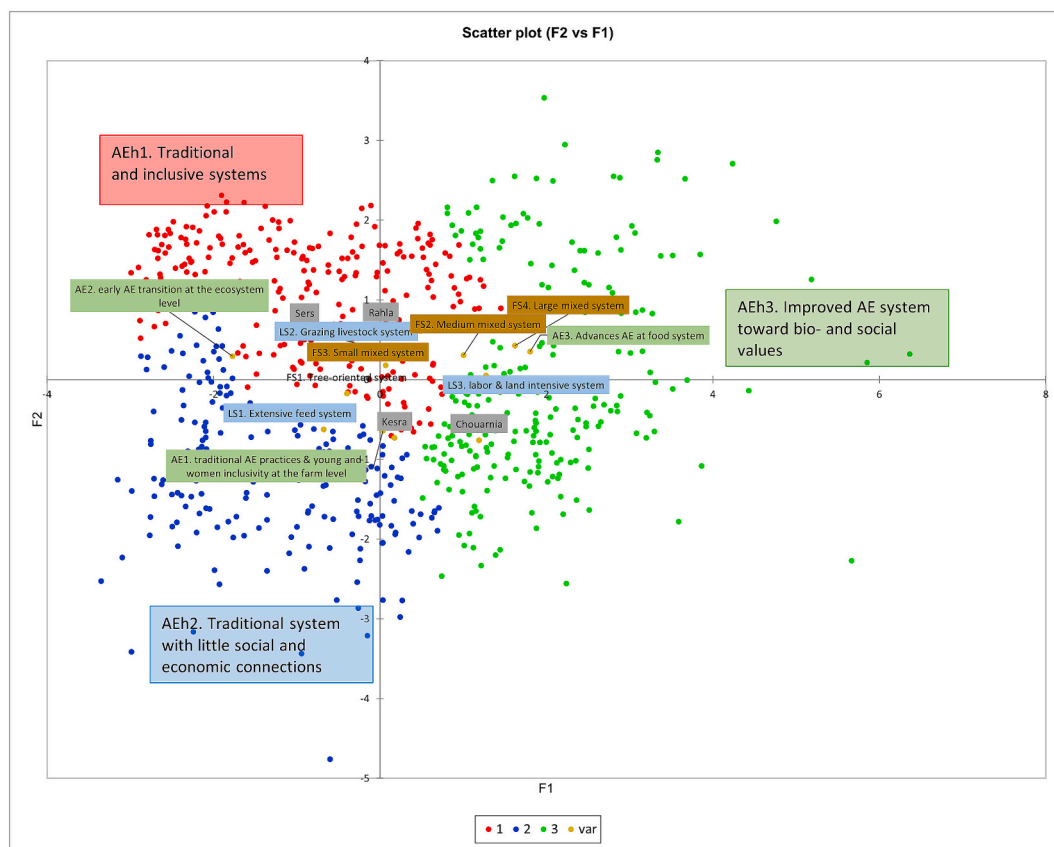


Fig. 7. Projection of farming system types, livestock integration types, and agroecology profiles based on the FAO's 10 elements approach on the first two factorial axes defined the agroecological profiles based on the 13 principles defined in the HLPE-13 principles frame (F1 and F2).

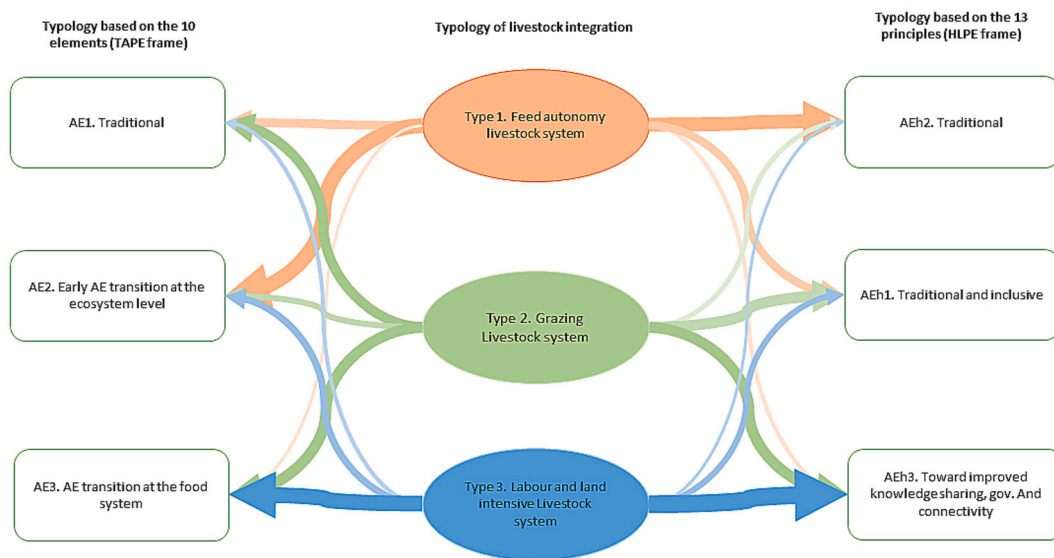


Fig. 8. Percentage of livestock integration systems in each agroecological profile identified respectively according to the 10 elements in the FAO frame (FAO, 2018) or the 13 principles of the HLPE frame (HLPE, 2019) (the width of the arrow represents the percentage of farmers of each type that fall within the agroecological categories).

people in livestock management concerns mainly traditional mixed CL farm systems. In such a system, a gender and social inclusion strategy should be considered as key for reinforcing the agroecological principles of synergy, in line with local knowledge.

The results also provide insight into how agroecological transformation aligns livestock integration with sustainable agricultural

principles, such as recycling, efficiency, and biodiversity, as highlighted in the FAO and HLPE frameworks (also well described by Martin et al., 2016). Livestock's role overtakes basic functions, contributing to ecosystem health through reduced external inputs, improved organic nutrient cycling, and enhanced biological synergies (Van Zanten et al., 2019). These systems also promote social equity and food sovereignty

by leveraging traditional knowledge and fostering diverse, resilient food systems that warrant further exploration (Röös et al., 2017, 2021). However, current agronomic approaches still underrepresent livestock's contributions, focusing narrowly on diversification and recycling. Comprehensive frameworks like FAO and HLPE can help demonstrate livestock's potential as a driver of systemic change, influencing both environmental and socioeconomic dimensions through synergy and resilience.

In summary, in North African contexts, as also demonstrated in other contexts of North Africa countries (Salem and Smith, 2008; Alary et al., 2020, 2022; Devkota et al., 2022), livestock integration within mixed crop-tree-livestock systems plays diverse roles, ranging from enhancing feed autonomy and soil fertility to supporting household nutrition and income. These contributions align with agroecological principles, driving transitions toward sustainable food systems. Also, as demonstrated in this paper, integrating livestock functions into broader frameworks, including socio-economic and food challenges, would allow mixed farming systems to serve as models for agroecological transformation. So, livestock emerges as both a functional and structural cornerstone, supporting the resilience, productivity, and sustainability of agroecosystems.

5.2. FAO's 10 elements and HLPE's 13 principles frames: Similarities and complementarities and methodological perspectives

The two considered agroecological frameworks (i.e., FAO and HLPE) share a common goal of advancing sustainable food systems through agroecological principles but emphasize complementary approaches. Both frameworks prioritize critical principles, such as biodiversity, recycling, efficiency, and synergy, to enhance ecosystem health and agricultural productivity. For example, FAO's focus on measurable elements aligns with HLPE's broad principles, emphasizing reducing external inputs, maximizing local resources, and improving biological interactions. These underlying mechanisms allow us to understand and explain the fundamental role of livestock in mixed farming systems, where the integration of crop and livestock activities embodies these shared principles by recycling nutrients, enhancing soil fertility, and increasing biodiversity.

However, a notable complementarity between the two frameworks concerns how they address the social dimensions. The HLPE framework explicitly links agroecological practices to governance, equity, and participation. The FAO's 10 elements framework operationalizes these social aspects by offering practical tools to assess and enhance local-level practices, such as co-creating knowledge and connectivity among stakeholders. This dynamic is especially significant in mixed farming systems in North Africa, where smallholder farmers depend on collective governance for shared resources, such as grazing lands, and where gender equity and local knowledge are crucial in decision-making processes.

While both frameworks aim to guide agroecological transitions, integrating them would yield a more holistic methodology. HLPE offers a broad, principle-driven perspective essential for setting systemic goals and evaluating transformative pathways, while FAO enables the practical evaluation and integration of agroecological practices (Wezel et al., 2020). Together, these frameworks create a comprehensive approach for sustainable farming systems, particularly in semi-arid mixed systems, where the interplay of livestock, crops, and trees demands strategic planning and context-specific action to achieve ecological, economic, and social resilience.

The approach and methods outlined in this paper allowed us to expand beyond the principle of crop-livestock integration to consider the various practices and intensities of integration. The present study focuses on the Tunisian agroecological living landscape (ALL), emphasizing localized, context-specific dynamics, including the biophysical characteristics and socioeconomic structures of the Kef-Siliana transect. This localized focus, coupled with the inclusion of smallholder mixed

farming systems dominated by cereal, tree, and small ruminant activities, highlights agroecology's adaptability to semi-arid zones. This contextualization enabled us to consider the diverse interactions between agroecological practices and specific environmental and cultural settings, as Ferguson et al. (2019) noted.

The study also introduces a range of partnerships and connectivity to address the influence of governance, participation, and local organization on agroecological transitions. By comparing farms with varying degrees of involvement in farmers' organizations, the present research links social dynamics, such as participation in cooperatives or extension services, to the early stages of agroecological adoption. This focus on social connectivity and institutional engagement as drivers of agroecological progress represents a significant advancement over conventional studies that prioritize biophysical or economic factors, yet neglect the sociopolitical dimensions of agroecological transformation.

Lastly, the study employs a multi-dimensional and principle-driven analytical framework that systematically aligns data collection with agroecological principles. The semi-structured household survey captures a comprehensive range of variables related to FAO's 10 elements and HLPE's 13 principles of agroecology, thereby extending the existing literature by providing a detailed, measurable linkage between farm-level practices and overarching agroecological frameworks. Additionally, the use of factorial and clustering analyses to establish typologies of farms and livestock systems along agroecological gradients provides actionable insights into how agroecological principles translate across diverse farming realities, and what possible transition pathways can or need to be developed for a more effective agroecological transition in livestock-based systems. By identifying groups of farms that share similar structural characteristics, resource endowments, and management practices, these typologies can help local and regional development agencies design more targeted interventions and support mechanisms. Furthermore, assessing the strengths and weaknesses of each farm type with respect to the different agroecological principles enables identification of the key factors driving or constraining agroecological transitions. Such knowledge can guide policymakers and development practitioners in prioritizing investments, extension services, and capacity-building efforts that address the most critical barriers while building on existing agroecological assets within each farming system.

In our work, we used a set of variables to define the levels for each principle, some of which are common to defining the farming system typology. However, the factorial analysis helped avoid relying on direct correlations by using linear combinations of variables that better discriminate between the different types. Furthermore, the combination defines the types compared in the analysis. Nevertheless, each principle or element underpinning agroecological practices presents challenges regarding meanings, definitions, and interpretations, as Wezel et al. (2020) already showed. The present study demonstrates that each principle can also vary in its delineation, configuration, and meaning within a specific context. Their interpretation often shifts depending on whether the perspective is rooted in agricultural technical approaches or social science frameworks. This variability underscores the complexity of applying agroecology across diverse systems and disciplines.

6. Conclusion

In conclusion, this study highlights the crucial role of livestock in driving the agroecological transition within mixed crop-livestock systems, particularly in the semi-arid regions of North Africa. The integration of animals with crops and trees has been shown to enhance nutrient cycling, improve ecosystem health, and support rural livelihoods by increasing resilience and resource efficiency. In this way, livestock contributes significantly to agroecological principles such as recycling, diversity, and synergy by utilizing crop residues, supplying organic manure, and supporting biodiversity through grazing. Furthermore, the study highlights the cultural and socioeconomic roles of

livestock, establishing it as a fundamental element in developing sustainable food systems that are environmentally sound, socially equitable, and economically viable. However, the present study also reveals weaknesses in this integration at the local level, primarily due to the need to strengthen the levers of synergy and the circular economy from a social perspective, which necessitate improvements in local governance.

Finally, the methodologies employed in this research, including the use of multi-dimensional frameworks such as FAO's 10 elements and HLPE's 13 principles, provide a comprehensive approach to assessing agroecological transitions in farming systems. The study addresses the discrepancy between global frameworks and on-the-ground realities by combining localized analyses of farming and livestock systems with broader principles of agroecology. The findings underscore the significance of social connectivity, governance, and knowledge sharing in promoting agroecological practices. In conclusion, integrating livestock into agroecological systems in the dryland areas represents a transformative pathway toward sustainable agriculture. This approach offers a replicable model for other regions facing similar environmental and social challenges.

CRedit authorship contribution statement

Véronique Alary: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Aymen Frija:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Funding acquisition, Conceptualization. **Sarah K. Jones:** Writing – original draft, Methodology. **Hassen Ouerghemmi:** Formal analysis, Data curation. **Zahra Shiri:** Software, Investigation, Conceptualization. **Zied Idoudi:** Visualization, Methodology, Investigation. **Hatem Cheikh M'hamed:** Supervision, Methodology, Investigation.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agsy.2026.104903>.

Data availability

Data will be made available on request.

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