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Principles, barriers and enablers to agroecological animal production systems: a qualitative approach based on five case studies

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ABSTRACT

Agroecology is among the most promising options to alleviate the negative impacts of animal farming on the environment and build local food systems based on ethically acceptable production methods. So far, most of the research on agroecological animal production systems was conducted at farm scale, and the potential of agroecological principles addressing social dimensions and food system–level approaches has been underexplored. Here, we analyse how the whole set of agroecological principles was mobilised in five case studies on grassland-based, silvopastoral or integrated crop-livestock systems in Switzerland, Guadeloupe, French uplands, Bulgaria and Andalucía. Following a multilevel perspective, we propose a new eight-category framework to categorise barriers and enablers in these different socioecological contexts, and discuss the implications of these results for scaling out and scaling up agroecological niche innovations in animal production areas. Though we could observe activities related to each agroecological principle in each case study, the relative importance of each principle differed. For instance, in Switzerland, the focus was on ecological processes operating in multispecies mixtures, and therefore on mobilising principles of input reduction, synergy, soil health and biodiversity, while in Andalucía, a civil society organisation, a regional agricultural office, researchers, and farmers mainly mobilised transformational principles at the food system level, e.g. social values, connectivity and participation. Such contrasts highlight how agroecology allows different equilibria among principles, adapting to the needs of farmers and local communities. Inadequate infrastructure and lack of technology were frequently reported as barriers to agroecological transitions. Policy needs to go beyond the mere support of agroecological practices on livestock farms and adopt a systems approach looking downstream and upstream if it is to enable a large-scale agroecological transition with EU public policies. Market as an enabler was linked to direct sales and short distribution circuits, generating added value to the benefit of local communities. Most agroecological systems benefited from a positive image among citizens and consumers, but cultural barriers resulted from change in product characteristics, e.g. veal meat colour in dairy system that promote long-lasting cow-calf contact. All case studies were very advanced in the social dimensions of agroecology, and cooperation networks were always reported among the enablers for scaling out. The multiactor network approach fostered knowledge exchange between farmers, researchers and citizens, and allowed participants to share values. Long-term commitment from local practitioners is required

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so that co-designed solutions are implemented, which can strengthen the economic and social viability of animal production areas.

Implications

Agroecology not only refers to the application of ecological theory and principles to design sustainable agricultural systems but also emphasises social and political aspects including community organisation, autonomy, and access to land. Here, a qualitative approach based on five case studies on grassland-based, silvopastoral or integrated crop-livestock systems aims to make the application of agroecological principles to animal production systems more tangible and concrete. We also propose a new eight-category framework to categorise barriers or enablers for scaling out agroecological animal production systems, which aims to be generic enough to allow comparison with further case-study analyses.

Introduction

Agrifood systems must undergo a radical transformation to evolve towards greater resilience and reverse or prevent the transgression of safe and just Earth system boundaries. Animal production systems (**APSs**) have received particular attention due to their negative impacts on climate change and perceptions of what constitute ethically acceptable production methods. Life cycle assessment studies using indicators based on impacts per kg of product, have ranked beef, lamb and dairy products among the foods with the highest environmental impacts in terms of greenhouse gas emissions, land use, terrestrial acidification, eutrophication and freshwater withdrawal (Poore and Nemecek, 2018). Despite these products having consistently higher impacts than most other food groups, studies have also demonstrated that a large variation in impacts exists within APSs (Poore and Nemecek, 2018) and that some APSs (e.g., grassland-based ruminant production systems) provide a number of ecosystem services to other agricultural sectors or society (Bengtsson et al., 2019). There is therefore an ongoing debate about if and how to meet the growing demand for animal protein at a global scale (Doelman et al., 2019) and about the potential to increase the diversity of protein sources (Fraeye et al., 2020) to be produced while staying within planetary boundaries.

In this debate, agroecology is among the most promising options to achieve food systems sustainability and food security, as it not only addresses production and environmental impact improvements but also considers fairness, equity and food system governance (Bezner Kerr et al., 2021). Agroecology proposes to work with nature and combines a diversity of scientific disciplines, movements and practices. The scientific dimension of agroecology applies ecological theory to the design and management of sustainable agroecosystems and food systems. It aims for agricultural systems that are productive, environmentally friendly and less dependent on chemical inputs by maximising natural processes. To do so, it opens a dialogue with local and traditional knowledge promoting on-farm diversity of plant and animal species so that the optimisation of interactions among system components is mobilised to enhance agroecosystem functions and resilience (Dumont et al., 2020; Tittonell, 2023). Within agroecological APSs, several management practices aim to recouple the carbon and macro-nutrient cycles by (i) manipulating both grassland primary production and stocking density and (ii) reconnecting crop and livestock to enhance circularity at the farm (Dumont et al., 2013) or regional level (Alvarez-Rodriguez et al., 2024). Agroecological thinking in APSs also implies understanding the relationships between farm animals and their pathogens, and to make the best possible use of animal adaptive capacities (Dumont et al., 2013). For domesticated species, the conservation of a wide genetic basis calls to preserve local breeds that are well-adapted to specific environmental and management conditions (Leroy et al., 2024). As a movement, agroecology promotes food sovereignty, local autonomy, and community control of land, water and genetic resources to facilitate the implementation of knowledge and social innovations in line with the scientific dimension of agroecology (Altieri and Nicholls, 2017). From a transition perspective, agroecology works on different aspects, from efficiency gains, to input substitution and ultimately food system redesign (Gliessman, 2007), in which production goals shift from the maximisation of outputs per animal or per unit area to the creation of added value at the farm or community level.

In 2019, the High Level Panel of Experts (**HLPE**) on Food Security and Nutrition of the Committee on World Food Security (HLPE, 2019) proposed a consolidated list of 13 generic agroecological principles as part of transition pathways to more sustainable food systems. These 13 principles were organised around three constitutive principles of sustainable food systems: (i) improve resource efficiency; (ii) strengthen system resilience; and (iii) enhance social equity and responsibility (HLPE, 2019). So far, most of the research on agroecological APSs was conducted at farm scale (e.g., Prache et al., 2023) and explored the application of ecological processes to animal, feed resource and farm system management (Dumont et al., 2020). This emphasis on the farm-scale has meant that the potential of the whole set of HLPE principles has been underexplored, especially in relation to principles addressing social dimensions and agrifood system–level approaches through co-creation of knowledge.

Here, we analyse how all 13 HLPE principles have been mobilised in five case studies on grassland-based, silvopastoral or integrated crop-livestock systems across Europe. The focus on these case studies ranges from agroecosystem (plot and farm) management up to the agrifood system level. In each case, practitioners and researchers have been engaged for several years in agroecological transitions and/or reflection processes on how to preserve smallholder farms, and forms of consumption aligned with agroecology. The objective of this article is to give concrete expression to the principles proposed by the HLPE by analysing how they have been jointly implemented in different socioecological contexts. Following the multilevel perspective of Geels (2002), we analyse how these contexts affect the implementation of principles, and act as barriers or enablers for scaling out and scaling up agroecological APSs. We propose a new eight-category framework to categorise these barriers or enablers. In the next sections, we introduce the conceptual framework we used for analysing the case studies. After describing the case studies' context, we describe how we characterise them in terms of the conceptual framework and discuss the implications of these results for unfolding agroecology in APSs.

Material and methods

Conceptual framework for analysing agroecology in animal production case studies

The 13 principles proposed by the HLPE (2019) are well-aligned with the 10 elements of the Food and Agricultural Organization of the United Nations (**FAO**) that have been approved by all member countries to guide FAO's vision on agroecology. The principles of the HLPE, however, explicitly refer to soil health (Domínguez et al., 2023) and animal health (Dumont et al., 2013) in agroecosystems, and distinguish between biodiversity and economic diversification, whereas these aspects are combined as one element, diversity, in the FAO framework (Wezel et al., 2020). At food system scale, the HLPE principles emphasise fairness, connectivity (i.e., re-embedding systems into the local economy) and participation (i.e., promoting decentralised governance and local adaptive management of the food system). Synergies and co-creation of knowledge are two principles, which appear as central in both frameworks (Wezel et al., 2020). Synergies enhance positive interactions amongst agroecosystem components (e.g., plant species in mixtures, co-grazing animals, companion plants repelling insect pests, etc.). Co-creation of knowledge implies the co-development of practices by involving farmers in collaborations with the scientific community and other stakeholders, including consumers, using a diversity of participatory approaches aimed at fostering the development of a shared vision of the issues and objectives to be achieved. Social learning and/or co-design of innovative farming systems through learning loops is key in the learning process (Rossing et al., 2021). Co-creation of knowledge implies (i) integrating farmers' values, perceptions and practices; (ii) accounting for the specificities of the local production system to be transformed; and (iii) disseminating knowledge among local communities and regional stakeholders. Horizontal sharing of knowledge based on farmers', scientists' and citizens' perceptions and values, farmer-to-farmer exchange, and greater participation of NGOs and civil society in decision-making is assumed to facilitate the transition towards sustainable APSs (Rosset et al., 2011; Dernat et al., 2022).

Scaling out of agroecological niche innovations is hampered by the existence of a range of lock-ins in unsustainable socio-technical regimes, including asymmetries in political and economic power. Lock-ins occur when the spread of an innovation that is advantageous for many farmers is hampered by the economic and technical strategies already in place in the farming system, and in the upstream and downstream sectors (Geels, 2002). In his multi-level perspective on transition, Geels (2002) identified policy, market, infrastructures, technology and stakeholder networks but also lack of knowledge (on agroecological systems) and culture as key dimensions that support and maintain dominant socio-technical regimes. In turn, global societal perception, such as the need to respond to social and environmental concerns, can put pressure on a dominant socio-technical regime and thereby create opportunities for changes towards better−performing systems. These changes are fed by a constant flow of niche innovations, some of which might, over time, anchor into the dominant regime by taking advantage of windows of opportunity. More recently, Anderson et al. (2019) also identified critical domains of transformation for sustainable food systems through agroecology based on a bottom-up approach, highlighting additional social dimensions including access to natural ecosystems, and equity. Here, we merged elements of both Anderson et al.'s (2019) and Geels' (2002) classifications to identify lock-ins and opportunities that can modulate the relative importance of HLPE principles in building the case studies' identities. The result of this merger led us to consider the following eight categories to inform barriers and enablers: (i) policy, (ii) market, (iii) infrastructures, (iv) technology, (v) cooperation networks, (vi) access to natural ecosystems, (vii) culture, and (viii) equity.

Case study description

We studied how the 13 HLPE agroecology principles materialised in the context of five Innovation Hubs that were part of the Horizon Europe Project Agroecology-TRANSECT (Transdisciplinary approaches for Systemic economic, Ecological and Climate change Transitions). The term Innovation Hub (**IH**) was used in the Project to indicate existing local networks, in which work on implementing and scaling agroecological practices at field and farm scales had been going on for at least 4 years before the Project's start. The networks locally connect researchers with other actors to co-develop actionable knowledge (Geertsema et al., 2016) and innovation strategies (Morel et al., 2020). Rather than only being the object of the Project's analysis, the IHs also contributed to the co-design of the Project's activities. Some IHs explicitly subscribed to agroecological principles, others operated around specific notions like crop or animal diversity, animal welfare, or high nature values. The IHs became part of the Project after a selection process in which in multiple interview rounds the alignment of the ambitions of the IHs and the Project were compared and negotiated. While the Project comprised 11 IHs, here we focus on the five that represent animal production systems based either on grasslands (Switzerland, Massif Central in France and Western Stara Planina in Bulgaria), silvopastoralism (Andalucía, Spain) or the integration of plant and animal production (Guadeloupe, French West Indies). These five IHs represent gradients in the scale of working, from plot to agrifood system levels, and in the importance of socio-economic and institutional factors compared with agronomic factors.

Data gathering procedures and analytical approach

Data gathering procedures followed three main steps: (i) inventory of practices implemented by each IH in relation to the 13 HLPE agroecological principles, (ii) ranking of the importance of each principle driving activities and goals in the IHs, and (iii) identification of barriers and enablers to the scaling out of agroecology in the IHs. In step 1, the agroecological practices implemented by each IH in relation to the 13 HLPE agroecological principles were documented during a 45-minute session held with one to three central actors of each IH (hereafter referred to as IH facilitators) and two Project scientists as part of a Project workshop. The IH facilitators are key actors and knowledge brokers (Harvey et al., 2012) in the sense that they have a good overview of the history and of the activities and experiments that have been conducted in the IHs, good knowledge of associated scientific literature, and act as facilitators not only within the IH but also between the IH and the Project. They first had around 15 min to familiarise themselves with the agroecological principles, guided by the definitions provided by the HLPE, and to reflect on the practices implemented within their IH. The reflection on the practices then continued in a 30-minute discussion with the two Project scientists facilitating the activity. The results of this data gathering activity are summarised in Tables 1–4, as a basis for a comparative analysis across the IHs.

In step 2, IH facilitators were provided with an empty spider-web diagram and were invited to self-assess the importance of the 13 HLPE principles in relation to IH activities and goals, with scores ranging from 0 to 3, as follows: principle is absent in current IH activities (score 0), principle exists but is marginal in current IH activities (score 1), principle is important in current IH activities, but is not shaping its overarching goal (score 2) and principle is shaping the overarching goal of the IH (score 3). In addition to these scores, the IH facilitators had the opportunity to add qualitative comments where appropriate, which were then used to make sense of unexpected answers. This activity built on step 1 by providing the IH facilitators with the list of practices documented in step 1. The self-assessment took place during a 30-minute session in a Project workshop one year after step 1. The combination of the scores and qualitative comments resulted in a qualification of the HLPE agroecological principles for each IH (Fig. 1).

Table 1
Summary of how the agroecological principles on Recycling, Input reduction, Soil health and Animal health (HLPE, 2019; Wezel et al., 2020) are translated into practice in the five Innovation Hubs.

Item	Swiss certified mixtures (Grassland-based)	Guadeloupe (Crop-livestock)	French Massif Central (Grassland-based)	Western Stara Planina, Bulgaria (Grassland-based)	Sierra de Aracena, Andalucía (Crop-livestock)
Recycling	• Value of leys for follow-on crops in the rotation: effects of residual N	• Feed ruminants at pasture, and broilers outdoors and from farm residues • Composting	• Use of manure • Heat recovery from the milking circuit	• Use of manure • Composting • Handicrafts in wool or wood	• Animals are grazed in agroforestry systems • Timber used for heating
Input reduction	• N_2-fixing species by legumes from multispecies mixtures • High forage quality limits concentrate use • Mixtures suppress weeds, with a follow-on effect in rotations	• Reduction in mineral fertilisation, anthelmintics and pesticide use • Sugarcane straw and banana leaves used as mulch for weed management	• Grass-based diets to reach feed autonomy at farm level • No mineral fertilisation thanks to N_2-fixing legumes • Limit antibiotics and anthelmintic	• Grass-based diets limit the use of concentrate feed • Use of N_2-fixing legumes • Practices aim to maximise fodder production on farm	• Grazing ruminants drastically reduces the use of concentrate feed • Pigs are grazed in chestnut and oak areas to fatten them
Soil health	• Forage mixtures benefit soil structure, organic matter and microbial community	• Low soil tillage • Soil coverage with mulch • No or small mechanisation to limit soil compaction • Soil amendment with fresh animal excreta or compost	• By minimising the turning over of permanent grassland, a large stock of organic matter is maintained in the soil	• Rotational grazing on pastures is assumed to benefit dung beetles and soil health • Green cover crops are used in crop rotations	• Traditional management practices aim at water retention and infiltration in the soil and aquifers
Animal health	• Multispecies mixtures with species containing condensed tannin • Testing mixtures to not contain anti-nutritional compounds	• Use crop secondary metabolites to manage strongyles in small ruminants • Curative approaches with papaya, banana and cassava leaves • Early detection of diseases by looking at animal eyelids	• Late separation of calf from dam • Slaughter young animals is non−ethical • Crossbred with a local breed to limit the energy deficit after calving, mastitis and locomotion disorders	• Grass-fed livestock farming and grazing is perceived as positive for animal welfare • Use herbs and nematophageous fungi to complement veterinary products	• Grazing under tree shadow benefits animal welfare

Table 2
Summary of how the agroecological principles on Synergy, Economic diversification and Social values and diets (HLPE, 2019; Wezel et al., 2020) are translated into practice in the five Innovation Hubs.

Item	Swiss certified mixtures (Grassland-based)	Guadeloupe (Crop-livestock)	French Massif Central (Grassland-based)	Western Stara Planina, Bulgaria (Grassland-based)	Sierra de Aracena, Andalucía (Crop-livestock)
Synergy	• Increased forage yield in multi-species mixtures • Temporal and spatial complementarities among grass, legume and forb species • Increased drought resistance thanks to the diversity of traits	• Mixed grazing • Companion plants attracting pollinators and crop auxiliaries (micro-hymenoptera) and repelling insect pests • Different layers of vegetation enhance resilience to drought and extreme events	• Grassland diversity at farm scale enhances management flexibility • Cultivating upland cereals on farm for straw and grain	• Multispecies grazing systems in dairy, beef and sheep farms • New products combine productions from farms and forest (e.g., cheese with herbs or berries)	• Mixed grazing: goat, sheep, pig, donkey, horse in agro-forestry systems • Planting other tree species in or between plots in traditional chestnut, olive and oak systems
Economic diversification	• Development of seed mixtures for restoring grasslands with a high biodiversity illustrates activity diversification • Promoting a wide range of multi-purpose mixture types	• Diversification of products, including high-value products: vanilla and aromatic herbs • New sale and distribution channels	• Use of dual–purpose crossbred for milk and meat • Creating a new product: locally fattened dairy calves that are slaughtered older	• On-farm processing and direct sales • Attempts to label farmer products • Handicrafts in wool or wood • Forest fruits, jams, teas	• Diversification of products: goat cheese, chestnuts, mushrooms, herbs • Expected investments in public infrastructures for transformation
Social values and diets	• Mixtures help maintain economic activities and cultural open landscapes in marginal mountain areas	• Microfarms provide culturally appropriate diets, including the crops and varieties cultivated by native communities • Participatory culinary workshop to bring Guadeloupe's local meats back into fashion	• Grassland-based systems shape the open, cultural landscapes of French Massif central (Protected Designation of Origin cheese, heifer transhumance, etc.)	• Farmer markets and local food festivals • Diversification centring on traditional products and some innovative cheese products • Cultural landscape with a mosaic of grasslands and forest	• Traditional peasant-like farming for household consumption • Cultural landscape shaped by agrarian tradition • Murals by local artists to support local pride in traditional agrifood systems

Table 3
Summary of how the agroecological principles on Biodiversity, Land and natural resource governance and Co-creation of knowledge (HLPE, 2019; Wezel et al., 2020) are translated into practice in the five Innovation Hubs.

Item	Swiss certified mixtures (Grassland-based)	Guadeloupe (Crop-livestock)	French Massif Central (Grassland-based)	Western Stara Planina, Bulgaria (Grassland-based)	Sierra de Aracena, Andalucía (Crop-livestock)
Biodiversity	• Maintaining genetic diversity in the seed production process by using various Swiss ecotypes • Selling seed mixtures with more than 40 species allows restoring degraded grasslands. • Training farmers on biodiversity	• Conserving genetic diversity by preserving local breeds: Martinik sheep, Creole goats and pigs • Connectivity of multistrata farms with forest benefits biodiversity by creating ecological corridors	• Temporarily ungrazed plots and late cut enhance pasture flowering intensity and benefit insect diversity • Hedges disturb vole galleries and provide habitat for predators • Preservation of local Ferrandaise breed	• Extensive grazing by cattle and sheep preserves habitats for biodiversity and tourism • Preservation of landscape features • Preservation of local sheep breeds	• Heterogeneous mosaic of agro/silvopastoral systems at the landscape scale • Grazing in wooded areas prevents running fires • Preservation of local breeds of pigs, sheep and goats
Land and natural resource governance	• Quality label for mixture certification • Providing advice to Federal Office for Agriculture if new grassland management rules are implemented	• Microfarms have the potential to feed more people than the regional average	• Co-design of ecological rotation with Regional Park • Protected Designation of Origin (PDO) specifications prohibit detrimental management	• Allocation rules for municipal grasslands • Testing result-based agri-environmental schemes • Legislation for on-farm processing and sales	• Cultural landscape is shaped by agrarian traditions • Landscapes and species diversity are protected under Natura 2000 initiatives
Co-creation of knowledge	• Practitioner board • Synergy with seed companies: gains from the label invested in variety testing, development of new mixtures • Test of mixtures from seed companies under a wide range of growth conditions	• Practices and local varieties tested in INRAE microfarms are collectively chosen by local farmers and researchers • Coupled with on-farm trials at farmers' sites and experimental farms	• Inclusion of citizens in participatory approaches enables accounting for their values • A grassland typology was built with PDO cheese board • Game-based learning approaches to design new systems	• Cross visits to other peers or abroad • Connecting farmers with biodiversity and grassland experts • Film in partnership with farmers and the Bulgarian Society for Protection of Birds • Phytotherapy adds to veterinary products	• Local farmers are considered as experts and involved in training • Collaboration with local agricultural officers to design new public infrastructures for local agrifood transformation

Table 4
Summary of how the agroecological principles on Fairness, Connectivity and Participation (HLPE, 2019; Wezel et al., 2020) are translated into practice in the five Innovation Hubs.

Item	Swiss certified mixtures (Grassland-based)	Guadeloupe (Crop-livestock)	French Massif Central (Grassland-based)	Western Stara Planina, Bulgaria (Grassland-based)	Sierra de Aracena, Andalucía (Crop-livestock)
Fairness	• Gains obtained from the certified mixture labels sold by seed companies are invested back into the development of new mixtures • Price at which quality-labelled seed mixtures are sold to farmers	• Microfarms aim at a fair share of the limited agricultural land area • They provide increased access to fresh fruit and vegetables by poor households	• Concerns with working conditions: possibilities for dairy farmers to take vacations (closing of the milking parlour), and benefits of once daily milking	• Policy support to High Nature Value farming including basic income payment and agri-environment schemes (AES) • Fair allocation rules for municipal grasslands	• Developing networking spaces between old locals and newcomers for mutual benefits • Facilitating events for women critical collective reflections
Connectivity	• Field days/exhibitions explaining grassland ecology to farmers and citizens • Technical information on mixtures provided in three languages	• Products from microfarms are sold to local distillery (sugarcane) and on local markets • Some unsold products (eggs) are donated to the food bank	• Promotion of i) short marketing chains (including new ones for calf fattening and slaughtering) and ii) Protected Designation of Origin cheese to enhance proximity between producers and consumers	• Farmers marketing in cities (direct sales) • Engagement in innovative marketing channels ("Feed from the mountain" brand) • Food for Talk visit in Bulgaria as part of the Good Food Good Farming initiative	• Strengthening farmer/consumer networks (e.g., local map of producers and retailers) • Supporting the development of agrifood transformation facilities
Participation	• Knowledge sharing and governance in multistakeholder platforms involving farmers, seed companies, researchers and extension services	• Local farmers were encouraged to participate in decision–making, while co-design Kréyol'Inov INRAE microfarm	• Inclusion of citizens in the construction of ethical calf management • Inclusion of two citizens on the management board of an INRAE farmlet experiment	• Local partnership in operational groups on agroecology involving farmers, NGOs and administration • Training of farmers to be knowledgeable and active partners	• Dynamisation of a multiactor network to strengthen the local agrifood system and retain added value locally • Facilitation of public events to collectively design the local agrifood strategy

In step 3, barriers and enablers to the scaling out and scaling up of agroecology in each IH were collated from background documents from the Project and informal communication throughout Project meetings and workshops. The documents included two Learning Histories, developed annually along the Project's duration by the IH facilitators (cf. Leclère et al., 2024), and an analysis of Innovation Hub "portraits". These portraits were constructed throughout the first two years of the project based on in-depth interviews with four to seven key actors in each IH, involving IH facilitators, farmers, and other stakeholders. They explored the history and current state of each IH and provided an initial mapping of barriers and enablers. The long-list of barriers and enablers was then refined by the IH facilitators through three iterative cycles with the lead author of this publication. This highlighted the importance of each category of barriers and enablers from our new classification, merging elements of both Anderson et al.'s (2019) and Geels' (2002) frameworks, for the unfolding of agroecology in APSs. A colour code based on a 4-step graduation was used in Fig. 2: red indicates barriers; orange indicates that elements in this dimension can act as either barriers or enablers for scaling out of agroecological niche innovations; green indicates that only enablers were reported during the interview, dark green highlighting that this enabler was of primary importance for the IH. The three steps were followed by validation and enrichment by the IH facilitators of the above data in two writing cycles, most notably by supplementing the respective results sections with references to supporting literature from each of the case study areas.

Results

Certified mixtures as an integrated part of sustainable forage production in Switzerland

With the third highest share of grasslands in the agricultural area of European countries, Switzerland is a grasslands country. The overarching objective of the Swiss IH is to promote grassland management systems based on ecological processes and enhanced multifunctionality. A specific goal is to use functional plant diversity to further develop the multispecies mixture system for leys in crop rotations and for the establishment of permanent grasslands. For instance, the number of species varies from six to 11 species in the mixtures developed for drought resistance in mountain areas. Each mixture for species-rich meadows has about 40 species. This certified mixture system is an integrated part of sustainable forage production and applies several agroecological principles.

Through functional diversity (related to HLPE principle on Synergy), multispecies mixtures increase forage yield over a wide range of relative species abundances in the sward (Nyfeler et al., 2009). The inclusion of legumes, with their ability to symbiotically fix di-nitrogen from the atmosphere, reduces dependency on external fertilisers (Input reduction; Table 1). The possibilities of further enhancing resource use efficiency by employing temporal and spatial complementarities among grass, legume and forb species are also explored (Input reduction, Synergy; Table 2; Husse et al., 2017). The high forage quality of grass-legume mixtures enables the reduction in concentrates in animal feeding with an

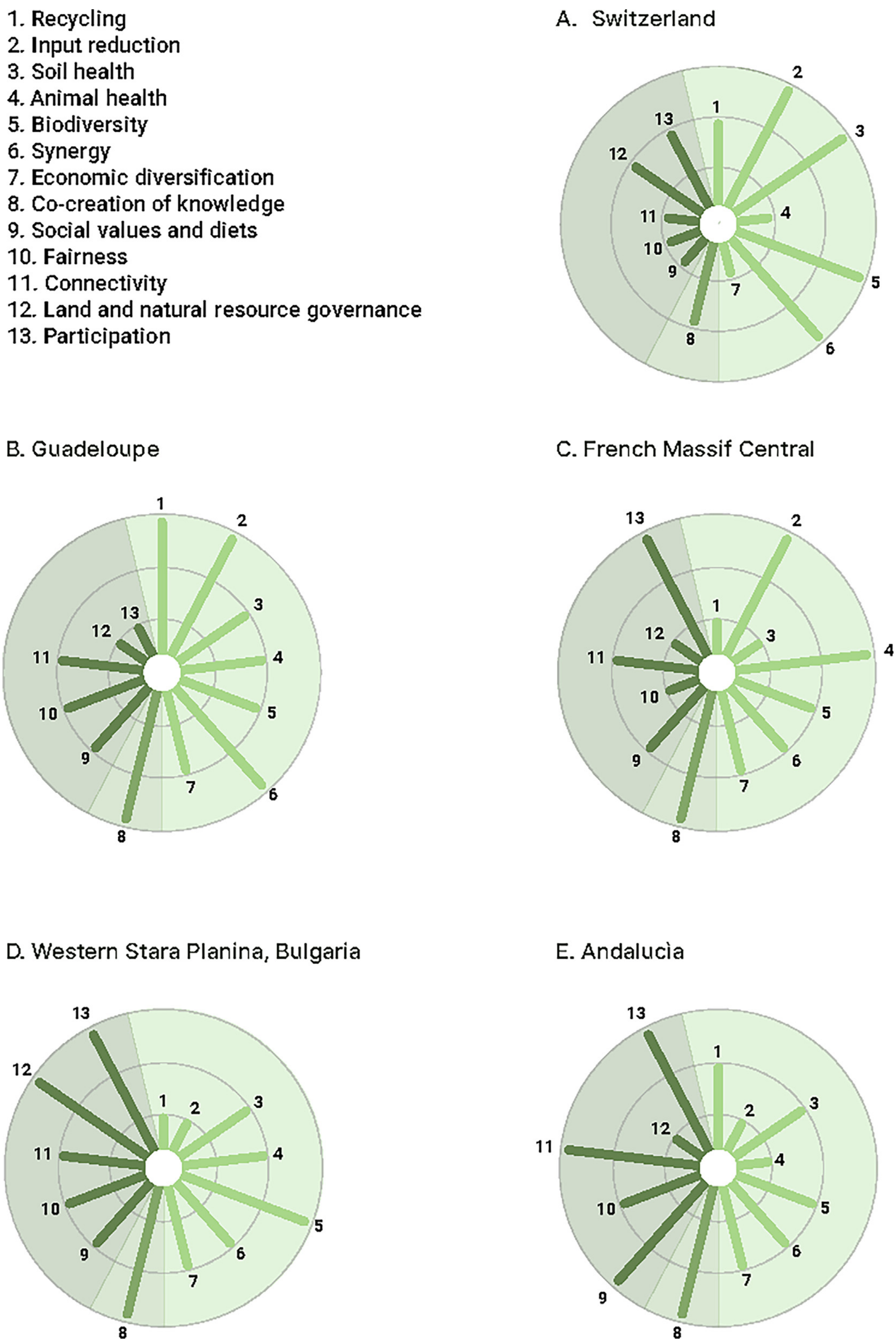

Fig. 1. Ranking of the importance of each of the 13 HLPE agroecological principles (HLPE, 2019; Wezel et al., 2020) driving activities and goals in the five case studies: a. Switzerland; b. Guadeloupe; c. French Massif Central; d. Western Stara Planina, Bulgaria; e. Andalucía. Score 1 (inner grey circle): principle exists but is marginal in current innovation hub (IH) activities. Score 2 (middle grey circle): principle is important in current IH activities but is not shaping its overarching goal. Score 3 (outer circle): principle is shaping the overarching goal of the IH. Bar colors represent the transition levels of each principle towards sustainable food systems, derived from Wezel et al. (2020), light green for those applying at the agroecosystem level, and dark green for those at food system level.

only modest adaptation in milk yield objectives (Input reduction). Plant species diversity has been shown to reduce vulnerability to climatic hazards and increase the drought resilience of permanent and sown productive grasslands, and increase the temporal stability of forage production (Lüscher et al., 2022). Multispecies mixtures, compared to pure stands, strongly suppress weeds, and thus are an important tool for integrated weed management (Input reduction). The use of species and ecotypes containing condensed tannins (Malisch et al., 2017) has the potential to reduce gastro intestinal parasite load (Animal health) and losses of nitrogen to the environment. Forage mixtures benefit soil structure, soil organic matter content (Guillaume et al., 2022), the soil microbial community (Soil health) and nitrogen availability (Recycling), leading to beneficial legacy effects on the follow-on crops in the crop rotation (Soil health) with little risk of nitrate leaching (Nyfeler et al., 2024). All seeds used in mixtures for the establishment of biodiverse grasslands originate from Swiss ecotypes and are produced to ensure within−species genetic diversity (Biodiversity, Land and natural resource governance; Table 3). Access to natural ecosystems is thus essential for producing these multispecies mixtures (Fig. 2) that are used to reseed degraded grasslands for conservation purpose and high−altitude grasslands damaged after recreation activities.

The Swiss IH functions as an umbrella organisation, uniting a diverse array of key stakeholders involved in grassland issues, including private seed companies, research institutions, extension services, educational entities, producers' unions, farmers, and public authorities. Existing since the 1930 s, it benefits from a strong historical foundation and is well rooted in the agricultural scene, thanks to its many activities covering the various stages involved in the co-creation of multispecies mixtures and their adoption by farmers (Co-creation of knowledge, Participation; Table 4). Because of the principles and ecological processes on which the Swiss IH bases the development of the mixtures, these mixtures are highly regarded in organic and alternative farming systems. Initially, new mixtures are developed and tested as replicated treatments in randomised, multisites experiments (e.g., development of new mixtures for mountain and drought stress). Promising mixtures are then tested under farm management conditions (strip trials at different agricultural schools and farms; Co-creation of knowledge, Participation). The mixtures resulting from co-creation with seed companies follow the same stages of evaluation that lead to acquisition of the certification label identifying mixtures with top performance and persistency under a wide range of management and growth conditions in Switzerland. The gains obtained from the certified mixture labels sold by seed companies are invested back into variety testing and the development of new mixtures (Fairness). Knowledge exchange is also achieved through the collaborative production of extension material (technical fact sheets, videos) and the holding of field days for and with farmers (Connectivity). Topics of interest are relayed at workshops organised with forage production advisors teaching at agricultural schools (relay and multiplier roles) along with various consultations for policies with federal offices.

The seed mixture quality label, which is managed by the IH and promoted by seed companies, offers opportunity for the scaling out of the use of certified mixtures (Fig. 2). Few players in the market facilitate its organisation. However, the high costs of producing seeds from quality varieties increase the costs for farmers. This could lead them to buy cheaper mixtures, which in turn would reduce investment in research and thus erode the system installed. Producing forage on arable land, such as on the Swiss plateau, could thus be threatened by future policies aiming to reduce feed-food competition. The magnitude of the impact of such policies will depend on counterbalancing efforts to maintain integrated crop-ruminant systems for promoting recycling and synergies. In Switzerland, the seed mixture sector benefits from the promotion of grassland-based milk and meat production (Fig. 2), and from the follow-on effects of grass-legume leys in crop rotations (Malisch et al., 2024). The above-mentioned benefits in the crop rotation are of tremendous importance to organic agriculture (Oberson et al., 2013) and therefore, political as well as consumers' support for organic agriculture are also viewed as enablers. Across the whole country, the attachment of consumers to traditional landscapes co-shaped by livestock farming (Schüpbach et al., 2021) illustrates how cultural dimensions appear among enablers.

Integration of crops and livestock in tropical microfarms from Guadeloupe

The Guadeloupe IH supports smallholder family farmers in adopting agroecological practices in tropical integrated crop-livestock systems. Small-scale family farming is characterised not strictly by a small area (farms are usually 2–5 ha), but also by its informal nature and the reliance on family labour. Guadeloupe faces an increased pressure on agricultural land due to demography, geographical limitations, rampant urbanisation, and long-lasting soil pollution by chlordecone, a pesticide that was used in banana plantations until 1993. Microfarms aim at a fair share of the limited agricultural land area (Land and natural resource governance, Fairness; Tables 3 and 4; Fig. 2). Nearly 85% of food consumption of Guadeloupe comes from imports. Guadeloupean agriculture is characterised by two contrasting agricultural models: on the one hand, export-oriented sugarcane and banana production and on the other hand small-scale family farming whose production feeds into the domestic market. For meat and egg production, there is a specialised industrial and often landless model with a high density of animals of commercial breeds or lines. On the other hand, small family farms are found with indigenous and/or crossbred animals that are grazed or fed on crop by-products. The two models represent 40 and 60% of cattle heads, respectively.

The overarching goal of the Guadeloupe IH is to demonstrate that agroecological practices in small-holder farms can mitigate the effects of climate change and provide farmers with a decent income, while preserving agrobiodiversity (Biodiversity). Central to this IH are two INRAE microfarms that count more than 30 cultivated species (Economic diversification; Table 2). These microfarms have been designed, evaluated and re-conceptualised since 2017, and allowed for multiple visits and presentations to practitioners and local decision-makers (Co-creation of knowledge, Connectivity; Selbonne et al., 2023). The co-design process of one of the two micro-farms is still ongoing between researchers and five farmers considered as pioneers (Fig. 2). Cultivars are selected for their drought and pest tolerance, while companion service plants (Canavalia, Cosmos, Tithonia) placed around banana trees attract parasitoid micro-hymenopterans that regulate banana pests (Synergy). Small ruminants, cattle, pigs and laying hens allow valorising co-products (banana by-products, sweet potatoes, cassava leaves and non-marketable products, . . .) and fallows, help managing weeds (Input reduction; Table 1), while providing manure to the cropping system (Soil health, Input reduction; e.g. Gourdine et al., 2018). Animals of Creole breeds (ruminants, pigs) are well adapted to heat stress (Animal health) and feeding on crop by-products. Multispecies grazing (Synergy) reduces strongyle load at pasture thanks to a dilution effect (Mahieu, 2013). Curative approaches can use papaya, banana, and cassava leaves to complement veterinary products (Input reduction; Marie-Magdelaine et al., 2010).

In the two INRAE microfarms, crop-livestock interactions offer many opportunities to increase productivity and resource use efficiency (Input reduction, Recycling). Farm autonomy and gross margin in one of the micro-farms were shown to be higher than the regional average (Selbonne et al., 2023). It has the potential to feed eight people per ha compared to three people per ha for the regional average (Selbonne et al., 2023). In commercial microfarms, interactions apply only to certain production types (e.g.,

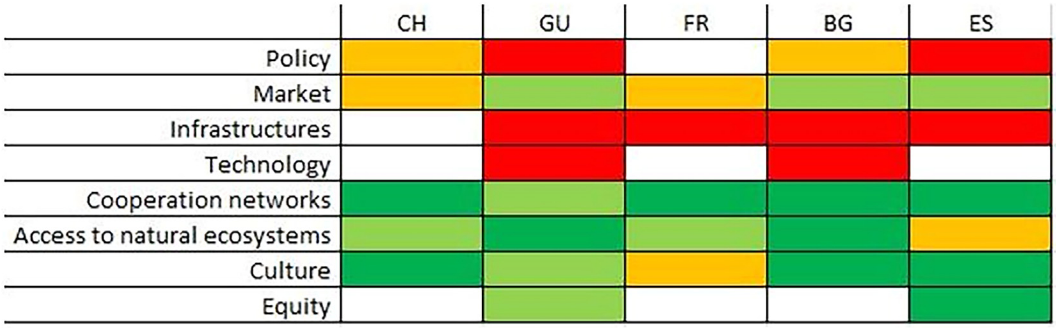

Fig. 2. Barriers and enablers to the scaling out of agroecology in each innovation hub (IH): a. Switzerland (CH); b. Guadeloupe (GU); c. French Massif Central (FR); d. Western Stara Planina, Bulgaria (BG); e. Andalucía (ES) according to the following eight categories framework: i) policy, ii) market, iii) infrastructures, iv) technology, v) cooperation networks, vi) access to natural ecosystems, vii) culture, and viii) equity. Red indicates barriers. Orange indicates that elements in this dimension can act as either barriers or enablers for scaling out of agroecological niche innovations. Green indicates that only enablers were reported during the interview, while dark green highlights that this enabler is of primary importance for the IH. Empty cells indicate that this dimension was not mentioned during the interviews (see data gathering procedure). Source: Geels, 2002; Anderson et al., 2019

feeding pigs with ill-shaped or overripe bananas; collecting ruminant manure for fertilising tubers in market gardens) rather than occurring at the whole farm level (Fanchone et al., 2022). Diversification of products, including high-value products such as vanilla and aromatic herbs, increases farmer income (Economic diversification). Products are sold locally (Connectivity), and enhance access to fresh fruit and vegetables by low-income families (Social values and diets, Fairness). Participatory culinary workshops were also organised to bring Guadeloupe's local meats back into fashion (Social values and diets). Finally, farms with several vegetation strata, including trees (Synergy) not only show high levels of production but also a faster productive recovery after a hurricane.

Access to land is a key concern in the insular context of Guadeloupe. The "one family living from one hectare" principle could therefore be seen as a guiding principle to co-construct transition scenarios at the territorial scale and guide policy design and implementation (Andrieu et al., 2022). Workload, work organisation, and some physically demanding activities act as barriers that limit the scaling out of diversified microfarms (Fanchone et al., 2022). Indeed, labour productivity is three times lower than the regional average (Selbonne et al., 2023), weed management being the most demanding activity since it represents 50% of the workload on an organic microfarm. Among the solutions to alleviate weed pressure is the use of grazing animals (e.g., sheep in banana plantations) or mulching (e.g., by recycling sugarcane straw or banana leaves; Recycling, Soil health). Other solutions foreseen are the development of adequate micro mechanisation and organisational innovations at the territorial level (i.e., sharing material or animals for weed control). However, machinery manufacturers have been slow to develop special machines for such a small market, which represents a technological barrier (Fig. 2). Mechanisation is also poorly adapted to product variability. Finally, platforms for storing animal excrement exist in Guadeloupe, but these infrastructures were not designed for a regular and mechanised collection of manure. Manure management is therefore done manually and is physically demanding (Fanchone et al., 2022), which limits manure distribution to cropping systems.

Another key barrier for the scaling out of small, diversified farms is that the policy support is primarily used by the integrated banana and sugarcane sectors (Fig. 2). Subsidies aimed at encouraging a transition to agroecological practices thus do not provide enough incentives for farmers to drastically change their system (Blazy et al., 2015). Innovative public policies including a collective bonus in addition to the basic payment could foster the transition. Such a collective bonus could be attributed as soon as farmers representing at least 50% of the area grown under the same type of cropping system adopt targeted agroecological practices. Another innovative policy could include administrative assistance and technical support for the implementation of innovative agroecological practices (e.g., compost use), which may increase their adoption.

Participatory research approaches for an ethical and sustainable dairy production in French uplands

In French Massif Central, the IH has brought together, since 2019, local farmers groups and associations, actors of the milk and cheese sector, actors in public policies, citizens and agricultural development, research and education institutes. The IH's goal is to develop an eco-citizen dairy farming system in the upland areas of Massif Central (Connectivity, Participation; Table 4). The image of upland pasture products is positive among consumers, but intensification of grassland management threatens biodiversity, and farmers face challenges such as adaptation to climate change, intergenerational transmission of farms (Allart et al., 2024), and farm profitability. Grassland-based systems shape open, cultural landscapes in French Massif Central (Fig. 2) and are important refuges for insect populations suffering from the agricultural intensification of lowland areas. An ecological rotation that avoided grazing some of the plots at flowering peak was initiated in collaboration with the regional park (Biodiversity, Land and natural resource governance, Co-creation of knowledge; Table 3) and is based on ecological theory, which predicts that increasing pasture heterogeneity and flowering intensity (i.e., trophic hypothesis) will benefit flower-visiting insects. Temporary removal of cattle from some plots at flowering peak led to a two-fold increase in butterfly and bumblebee populations, without decreasing farm stocking density (Farruggia et al., 2012; Ravetto Enri et al., 2017). However, it reduced by 20% the number of grazing days a year of poor spring grass growth (Farruggia et al., 2012), which confirms the agroecological notion that practices should be adapted to the seasonal and local context rather than being considered a one-size-fits-all strategy.

Grassland-based systems are, however, highly vulnerable to summer droughts that can drastically reduce forage yield. Preserving grassland diversity at farm scale is essential as the contrasting dynamics of biomass production across grassland types enhance flexibility in grassland management and can buffer the effects of droughts on forage yields (Synergy; Table 2; Carrère et al., 2021; Allart et al., 2024). The use of sown mixtures and of exotic species such as Eragrostis tef was tested to limit forage losses during summer droughts or after rodent damage. A grassland typology was also co-created between researchers, a protected designation of origin (**PDO**) cheese union, farm advisors and environmental NGOs, and a diagnostic tool was proposed to farmers to explore management strategies adapted to the types of grasslands present on their farms (Co-creation of knowledge). An educational game aimed to reveal the benefits provided by grassland–type diversity to cope with various climatic or socio-economic hazards (Carrère et al., 2021).

The Massif Central IH aims to co-create sustainable and ethically acceptable grassland-based dairy farming systems that are responsive to citizens' concerns for animal welfare (Co-creation of knowledge), e.g., late separation of the calf from the dam. Consumer awareness of the current fattening conditions of veal calves, which is associated with early dam-calf separation, could stop some of them from consuming veal meat and dairy products (Coeugnet et al., 2023). Early dam-calf separation is, however, still widely advocated as it induces less stress at the time of weaning and enables better control of colostrum and milk consumption. However, by measuring cortisol in the hair of calves, Pomiès et al. (2022) showed that dairy calves reared by their dam experienced less stress before and after weaning than artificially reared calves (Animal health; Table 1). Such knowledge was shared with farmers, researchers and citizens by Coeugnet et al. (2023), who adapted the knowledge-concept-proposal (**KCP**) design method (Le Masson et al., 2009) to promote dialogue between dairy farmers, stakeholders of the dairy sector (advisors, butchers, etc.), researchers and citizens (Co-creation of knowledge, Participation). The KCP design approach and the presence of citizens enabled the reduction of fixation effects, allowed for the sharing of values related to dairy farming between participants (e.g., slaughtering young animals was considered unethical by some of them), and ultimately led to co-designed innovative solutions, which, in some cases, would transform the veal-calf sector (Fig. 2). An example is an inter-generational calf fattening system, in which calves would be reared by nurse cows intended for culling, in a cooperative managed by farmers, whose products are sold locally (Connectivity, Economic diversification). Associating KCP and game-based learning approaches not only promoted horizontal sharing of knowledge among stakeholders but also put farmers and citizens in an active position to design innovative systems. One game session led to the inclusion of two citizens in the management board of an INRAE farming system experiment (Participation).

The economic success of practices allowing for the long-lasting suckling of dairy calves by their dams lies in two conditions: (i) a reduction in workload and/or physically demanding activities and (ii) an enhanced added value for the products (veal and/or milk) in these systems (Nicolao, 2022). An infrastructure barrier is that housing facilities are so far not adapted to long-lasting cow-calf contact (Fig. 2). The application of labels identifying animal welfare practices or cow-calf contact systems could be investigated to analyse opportunities for generating added value in these systems. Label efficiency is context-dependent, but as cows grazing in upland areas is part of the local cultural landscape, a label combining environmental and animal welfare dimensions could be a great success. Farmers acknowledged the positive image resulting from the long-lasting suckling of dairy calves by their dams. However, the milk suckled by calves comes at the expense of PDO cheese production, which generates high added value. The price that consumers would have to pay for this calf meat would therefore be probably high, which is a strong market-driven barrier to the development of cow-calf contact systems. An alternative would be to develop such systems in areas where milk is sold to dairies and less highly valued. Also, French consumers expected white veal meat, while animal welfare measures such as calf grazing result in pink veal calves. This highlights how cultural factors can act as both enablers and barriers in a given context (Fig. 2).

Empowering small livestock farmers in a high nature value area of Bulgaria

Western Stara Planina in Bulgaria represents a biodiversity-rich mosaic of forests and mountain grasslands with arable fields in lowlands and along river beds (Kazakova et al., 2017). Since 2014, the goal of the Bulgarian IH is to support the viability of the local High Nature Value (**HNV**) farming systems (Economic diversification; Table 2) created and maintained by grassland-based dairy, beef and sheep farms. The preservation of extensive, rotational and multispecies grazing (Synergy) is important for preserving soil health, flora (Aneva et al., 2020) and fauna (Concepción et al., 2020), including a number of species of patrimonial importance (Biodiversity; Table 3). The IH is centred on the collaboration of farmers, the Society for Territorial and Environmental Prosperity (**STEP**) and other local and national NGOs, researchers and administration (Participation; Table 4). Farmers' experience and local knowledge are valued (Co-creation of knowledge). The IH helps expand their capacity by providing training on biodiversity, marketing approaches and policy requirements. It also promotes cross-visits to other regions and countries (Connectivity) for on-farm discussions and round tables (Bernard et al., 2023). It shares experiences by showcasing videos based on farmer interviews, e.g. highlighting the benefits of extensive farming for wildlife.

Farmers graze their animals to benefit from abundant grassland resources, thus reducing the purchase of concentrate feed (Input reduction; Table 1) and contributing to animal welfare and product quality (Animal health, Social values and diets). Green cover and N-fixing crops preserve soil health in crop rotations that enhance feed autonomy on farm (Soil health, Input reduction). On a more occasional basis, farmers graze animals on pastures with mountain willow (Salix sp.) or Filipendula ulmari in spring and autumn. Both plants contain salicylic acid (aspirin), which farmers believe strengthens animal resistance to diseases. Farmers also gather Calvatia utriformis and give it to the animals due to its antiparasitic action (Animal health, Co-creation of knowledge). The literature confirms some evidence of the use of nematophageous fungi for the biocontrol of herbivore strongyles (Braga et al., 2009).

Either the State or municipalities own the majority of the grasslands. Prior to the accession to the European Union in 2007, grassland use was informal, farmers mostly using common grasslands nearest to their housing facilities. The EU Common Agriculture Policy required the introduction of clear and verifiable use rights. The setting up of a fair and equitable governance system therefore became a priority (Land and natural resource governance). The IH connected local farmers, agriculture administrators and experts (Co-creation of knowledge, Participation) and contributed to the design of allocation rules for municipal grasslands that favoured local livestock farmers (Fairness). Long-term access to common pastures allowed farmers to benefit from EU support of agri-environmental schemes and Natura 2000 payments (Fig. 2). The initial legislation, however, neither accounted for habitat type, nor recommended any stocking density in the allocation rate, which did not prevent a decline in the area of grassland habitats of community importance (Kazakova and Stefanova, 2022) and of their biological diversity (Pardo et al., 2020; Grigorov et al., 2022). More recent rules added an allocation criterion based on land productivity, but the overall result remains an unintended intensified use of the majority of HNV grasslands in the country. This illustrates how public policies can lead to unexpected barriers through their implementation (Fig. 2). Locally the IH, however, successfully pilots a result-based agri-environmental payment scheme (RBAPS; Land and natural resource governance) that contributes to biodiversity conservation in Natura 2000 protected sites. The biodiversity targets and implementation approach are co-designed by the farmers and experts in the IH (Co-creation of knowledge).

Members of the IH also explore direct marketing initiatives to enhance the viability of grassland-based dairy (cattle and sheep) and beef farms (Economic diversification; Connectivity). Farmers diversify both their products, e.g., cheese with wild berries or herbs, craft sheep wool decorations, wood craft (Synergy, Recycling), and their marketing channels, e.g., farmers' markets in cities and local food festivals, online sales and branding based on the slogan "Food from the mountain" (Social values and diets, Connectivity). Successful farms and initiatives, however, still remain at the niche level. Wider uptake and scaling out requires addressing barriers related to the lack of infrastructures such as slaughterhouses and dairy facilities to process smaller quantities (Fig. 2), or broadband internet for marketing needs and online customer service, as well as services such as snow clearing from mountain roads during winter. The lack of technologies adapted to small mountain farms (animal housing, on-farm equipment, etc.) is another important barrier, especially with farmers trying to address the demographic challenge by adopting new technologies when it is economically feasible. Cultural dimensions, including the increased urban consumers' interest towards local and farm products, are among the key enablers (Fig. 2), as illustrated by the success of local food festivals and the attachment to local animal products and traditional landscapes preserved by extensive grazing systems. The IH leaders from STEP also joined the "Good Food-Good Farming" initiative to set up a Food for Talk visit in Bulgaria. The event discussed sustainable food systems and was designed to send a message to the European Commission in the form of a short film, advocating for food and agriculture that work in favour of all people, biodiversity and climate (Connectivity).

Dynamisation of a multistakeholder network to increase socio-economic resilience in Andalucía

The Sierra de Aracena is a low−range mountain area (max. 1 040 m asl) at the western border of Sierra Morena in the Huelva province (Andalucía, Spain) that includes a total of 29 small municipalities. The Sierra de Aracena has a long history of low-input, diversified (Economic diversification; Table 2), increasingly abandoned (Navarro-Valverde et al., 2021), small-scale family farming and strong rural communities with a rich local society and cultural heritage around a mosaic of cultural landscapes (Biodiversity; Table 3). Cultural landscapes with a prominent touristic interest in the area (Bahamonde-Rodríguez et al., 2022) are strongly shaped by agrarian traditions (Social values and diets, Joffre et al., 1988), particularly around the iconic Iberian pig, chestnuts, mushroom diversity and homegardens (Ruiz-Ballesteros and Cácere-Feria, 2016). Almost one-third of the area is covered by agroforestry systems, while dense forests and Mediterranean sclerophyll shrublands cover another third of the area. These landscapes and species diversity are protected under several Natura 2000 initiatives, of which the most relevant is the "Sierra de Aracena y Picos de Aroche" Natural Park.

Smallholder farmers combine livestock with local breeds (Biodiversity, Economic diversification) such as Iberian pigs (including the endangered "manchado de Jabugo"), merino sheep, "blanca serrana" or "blanca andaluza", "negra serrana" and "murciana-gran adina" goat and cattle (Rodríguez-Estévez et al., 2004), as well as arable farming, producing food primarily for household consumption, except for cork, chestnuts and Iberian pig products, which are exported. Diversified grazing systems including pigs, small ruminants and cattle in silvopastoral systems dominated by oaks, chestnuts and olive trees are essential not only for food provisioning in an ecologically harsh region but also for wildfire prevention. Rearing animals with little or no input and under the shadow of the trees is a resilient practice in the face of a climate change that is producing increasingly dry, warm and long summers (Animal health, Input reduction; Table 1). However, while most public and private support is oriented to pig production, small ruminant and mixed farming systems (Economic diversification), including donkeys and horses that provide ecosystem services such as wildfire prevention (Synergy), are increasingly abandoned due to a lack of generational turnover and economic profitability. Access to natural ecosystems is very relevant in the Sierra de Aracena, where most land is private and crucial to maintaining pastoral activity with small ruminants (Fig. 2). Water management is also a key concern; traditional gravity-based water distribution systems (ditches, keyline) aiming at water retention and infiltration in the soil and aquifers are being recovered by newcomers adopting regenerative and agroecological farming approaches (Soil health; Land and natural resource governance). Recycling and synergy logics are inherent to these agroforestry systems, in which timber is extracted as the main household heating source and mushroom picking contributes to the local economy by attracting tourists and supporting the identity of the local gastronomy (Social values and diets, Economic diversification). However, interviews with local stakeholders have also revealed competitive relationships that create difficulties for the governance of sustainable tourism in Natural Parks (Bahamonde-Rodríguez et al., 2022). Public policies for nature conservation through the Natural Park also limit small-scale on-farm transformation on small ruminant farms (Fig. 2), while this was shown to be among the main assets of organic and agroecological systems across Europe (Benoit et al., 2023).

The IH Inspira Territorio is an alliance established in 2019 of local civil society organisations, small companies, research entities, a local development group, a regional agricultural office and municipalities (Participation; Table 4) in the Sierra de Aracena. Within Inspira Territorio, researchers, farmers and local agricultural officers (Co-creation of knowledge) are exploring enablers and barriers for local small-scale slaughter and transformation of meat and dairy (Fig. 2), among other products such as vegetables and olive oil (Economic diversification), at public infrastructures, including material means, training and legal coverage. This highlights the crucial role of infrastructures in scaling out agroecological APSs. Such an agrifood system perspective could enable the retention of added value within the region, with positive social and environmental outcomes (Fairness). Inspira Territorio is dynamising multiactor local networks to bridge locals' and newcomers' networks, and aims to collectively design a local agroecological agrifood strategy (Participation). It provides open space for women and young farmers with significantly relevant voices and leading innovative agroecological projects (Fairness). It also aims to facilitate visitors' and local inhabitants' access to local food products through a map of local producers (Connectivity) and supports local pride in traditional agrifood systems through an open-air museum of murals by local artists (Social values and diets).

The strong local identity on Iberian pig farming outdoors, associated to local transformation and direct sales of various animal products on local markets, appears among the stronger enablers to preserve these peasant-like forms of agriculture (Fig. 2), which is likely to generate added value to local communities and have greater societal support. The scaling out of agroecological APSs would require shifts in production systems and in the type of meat consumed. In Spain, opting for agroecological APSs would decrease pig and poultry consumption and production in intensive production areas such as Catalonia, and favour traditional pig fattening systems in wooded areas. This would also require a 70% increase in the consumption of small ruminant products (Aguilera and Rivera-Ferre, 2022), with sheep and goats mostly raised in extensive production systems.

Discussion and conclusion

We have analysed how the 13 principles proposed by the HLPE (2019) and Wezel et al. (2020) as guidelines to implement locally adapted agronomic and organisational innovations are mobilised in five case studies on grassland-based, silvopastoral or integrated crop-livestock systems, covering a wide range of socioecological contexts across Europe. This analysis aims to make the application of agroecological principles to animal farming systems more tangible and concrete, and to highlight principles addressing social dimensions and agrifood system–level approaches that have been underexplored in the animal science literature so far. In line with several recently published articles characterising agroecological systems in terms of alignment with the FAO elements (e.g., Lucantoni et al., 2023), all the HLPE principles were mobilised in each IH. This emphasises the fact that agroecology can be implemented as a systemic and global approach to APSs, and is not limited to the optimisation of one or a few ecological processes at farm or plot scale. Though we could observe activities related to each of these 13 principles in each IH, their relative ranking of importance differed among IHs (Fig. 1), which reveals contrasting entry points for building the IH's identity (Barrios et al., 2020). For instance, the entry point in Switzerland focused on ecological processes operating in multispecies mixtures (i.e., Input reduction, Synergy, Soil health and Biodiversity), while in Andalucía Social values and diets, Connectivity and Participation played a central role (Fig. 1). Such contrasts in the mobilisation of the different principles in the different IHs highlight how agroecology is giving space to different equilibria among principles, which makes sense for a concept that calls to adapt to the needs of farmers and local communities. These variations seem to be related to the focus of the different IHs: those focusing on a very broad group of farms mainly mobilised transformational principles at the food system level (dark green colour in Fig. 1), while the IHs focusing on interactions amongst agroecosystem components mainly mobilised the agronomic and ecological principles (light green colour in Fig. 1). Also, the relative importance of social equity and of re-embedding food systems into local economies, compared with agronomic dimensions, seemed higher in the areas where remuneration of farm workers was lower according to EC (2021) data. Finally, a principle could become marginal in an IH, as it proved irrelevant in a given context, e.g. input reduction in Andalucía and Bulgaria where the IHs included very low-input smallholder forms of animal production.

Co-creation of knowledge was central in all IHs and involved farmers and various other actors, such as local agricultural officers and extension services (Andalucía, Bulgaria, Switzerland), researchers (Bulgaria, Massif Central, Guadeloupe, Switzerland), producers' unions (Switzerland, Massif Central), private seed companies (Switzerland), environmental NGOs (Bulgaria), regional parks (Massif Central, Andalucía) and other public authorities (Bulgaria, Switzerland, Andalucía). Enhancing collaboration between farmers and citizens was central in the activities of Andalucía, Bulgaria, and Massif Central IHs, and in the latter, it led to a co-designed proposal that would transform the veal-calf sector (Coeugnet et al., 2023). A benefit of enhancing collaboration between farmers and citizens is illustrated by the innovative co-designed propositions following the inclusion of citizens (i.e., of non-traditional stakeholders) in the debate on sustainable dairy systems in upland areas. The project has, however, failed to materialise so far due to a lack of leadership and commitment from local practitioners, but in an area where PDO cheese is produced nearby, a 1-year co-creation process led to the proposal of a 10-year strategy by the PDO cheese union that was voted by its members and put into action since 2019 (Dernat et al., 2022).

The lack of follow-up in the French IH illustrates the challenge to implement and adopt innovations in spite of a co-creation approach involving both producers and consumers and aiming to support locally adapted food production systems. We therefore analysed the main barriers and enablers to the scaling out and scaling up of agroecological systems in the five IHs (Fig. 2). Several messages arose from this qualitative, transversal analysis. First, policy, inadequate infrastructures and, to a lesser extent, market and technological issues were frequently reported as being among the main disabling factors. Infrastructure lock-ins occur at the farm level but also upstream and downstream at the supply side (e.g., Morel et al., 2020) as a result of co-evolution of APSs with technology, public policies and market dynamics that have promoted specialised industrial APSs so far. The phenomenon has been analysed in the grain-legume sector by Magrini et al. (2016) and leads to economies of scale and increasing returns, which reinforce the dominance of specialised systems. In order to scale out agroecology, the focus needs to be on tailored innovations that fit the characteristics of APSs from the niches. For instance, the conception of mobile and multipurpose equipment such as modular racks, fences, etc. would facilitate the adoption of multispecies APSs such as those we analysed here in Bulgaria, Andalucía and Guadeloupe. Multispecies farms purchase feed in smaller quantities, implying that they do not benefit from economies of scale and face higher costs. On the supply side, cooperatives also have logistic systems based on centralisation and economies of scale. They could thus be reluctant to collect animals and products from multispecies farms that produce fewer animals of each type. To remediate the situation, the focus needs to be on the development of coupled innovations, in which organisational and technological innovations go hand in hand and depend on each other (Garrett et al., 2020). Attempts to set up a slaughterhouse for small ruminants were considered among the priorities of the Andalusian case study, which further highlights the crucial role of infrastructures in the scaling out of agroecological APSs. In the absence of interest by the dominant actors within the system, this type of innovation is promoted and set up by local farmers.

Market as an enabler was linked to direct sales or short distribution circuits in Bulgaria, Andalucía and Guadeloupe, which aligns with results from a previous analysis of multispecies, organic livestock farms across the EU (Benoit et al., 2023). Policy was more frequently recorded as a disabling factor than as an enabler across the five analysed IHs, and the Bulgarian IH illustrates how well-meant policies can introduce unexpected barriers through their implementation rules. Another barrier is the competition for policy support with the integrated production of banana and sugarcane in Guadeloupe, or pork meat in Spain that are not in line with agroecological principles, i.e., vested interests dominating the policy field (Place et al., 2022). Our analysis reveals that pro-agroecology policy needs to go beyond the mere support of agroecological practices on livestock farms and adopt a systems approach looking downstream and upstream if it is to enable a large-scale agroecological transition with EU public policies. Culture can act as either a disabling or an enabling factor. Many agroecological APSs benefit from a positive image among citizens and consumers, which was confirmed by the current study. Cultural barriers were mostly related to a lack of understanding by farmers of the benefits of implementing agroecological practices, and for consumers to changes in product characteristics, e.g. veal meat colour in innovative Massif Central systems. Animals fattened on grass-based diets in agroecological APSs sometimes have lighter and less homogeneous carcasses than currently required by industry. Benoit et al. (2019) have highlighted such a mismatch between the multiple performances of grass-based sheep farms and the industry demand for lamb conformation along with a regular supply throughout the year. Finally, access to natural ecosystems was key in Guadeloupe where there is strong competition for land, and in Bulgaria where the setting up of a fair governance system to allocate municipal grasslands has proved crucial to maintaining pastoral activity.

Overall, locally adapted innovations were assumed to provide a number of environmental and social benefits at the field, farm and food system levels. Some quantifications of the environmental and economic benefits were provided from plot (Farruggia et al., 2012; Ravetto Enri et al., 2017) up to farm scale (Schaub et al., 2020; Selbonne et al., 2023). However, our assessment of the benefits of adopting agroecological innovations remains largely qualitative so far, and one challenge will be to identify a set of appropriate indicators to quantify the benefits of agroecology in APSs, while maintaining a holistic approach on a large scale. Finally, beyond what we learn, the question of how we learn is crucial as part of a process of transition. All five IHs were very advanced in the social dimensions of agroecology, and cooperation networks (and in some IHs search for equity) were always reported as enablers for the scaling out. The multiactor network approach fostered knowledge exchange between farmers, researchers and citizens, and allowed for the sharing of values between participants (Page et al., 2016; Coeugnet et al., 2023). Ultimately, it aims to co-design solutions meeting both farmers' and citizens' expectations. However, while co-production processes in multiactor networks are assumed to contribute to the transformative change of agroecological systems, their actual transformative capacity remains unclear for now (Levidow et al., 2014; Jagannathan et al., 2020). As can be seen by the experiences described in the five case studies, we can at least state that one of the conditions for their success is the long-term commitment from local practitioners, which is required for the implementation of co-designed solutions.

Ethics approval

All central actors of each IH provided their informed consent to participate in the research and explicitly authorised the use of the results in the context of this study.

Data and model availability statement

No model was used for this article. Information can be made available from the authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

The authors declare no conflict of interest.

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Transparency Declaration

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