ANNUAL REVIEWS

Annual Review of Resource Economics

Agroecology for a Sustainable Agriculture and Food System: From Local Solutions to Large-Scale Adoption

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Annu. Rev. Resour. Econ. 2023. 15:351–81

First published as a Review in Advance on July 12, 2023

The *Annual Review of Resource Economics* is online at resource.annualreviews.org

https://doi.org/10.1146/annurev-resource-102422-090105

JEL codes: Q1, Q2, Q5

Keywords

sustainable agriculture, food system, multiple scales, multiactor approaches, agricultural policy, food policy, agricultural transformation, emerging technologies

Abstract

Agroecology is often considered as the ultimate and most comprehensive solution to the many challenges of the agricultural and food system, also referred to as the agri-food system. This review investigates to what extent agroecology can become the mainstream model for transforming agriculture toward more sustainable and resilient agri-food systems within the given economic and political context. We find that enhancing agroecology will require a fully integrated multiscale systems approach from farm to region to globe. The approach must consider relevant processes and relationships, actors and stakeholders as well as drivers, sustainability indicators, and the respective assessment methods across all scales. Giving specific attention to drivers related to economy, technology, and policy we point out that agroecology needs to be economically viable for farmers and other food system actors. In particular, new and emerging technologies related to digitalization and breeding should be given more consideration in agroecological transformation. We stress the need for an analytical and operational framework and adequate multiscale policy design and suggest six areas of needed attention to support the large-scale adoption of agroecology.

1. INTRODUCTION

Agriculture is facing tremendous challenges, including food security (FAO et al. 2022, HLPE 2020), climate change (IPCC 2022, Ortiz-Bobea et al. 2021, Trnka et al. 2014, Wheeler & von Braun 2013), loss of biodiversity (Brondizio et al. 2019), environmental pollution and resource degradation (Campbell et al. 2017, Steffen et al. 2015), as well as increasing price volatility (Chavas 2011) with harmful implications for farmers' incomes, livelihoods, and rural development. Crises such as COVID-19 (Barrett 2020, Carducci et al. 2021, Fan et al. 2021) and the Ukraine war (Behnassi & El Haiba 2022, Osendarp et al. 2022) have posed additional shocks to the resilience of the agricultural and food system (hereafter agri-food system) (Meuwissen et al. 2019, Nóia Júnior et al. 2022), with damaging impacts on prices, food security, and social stability.

Various concepts for different types of agriculture have been developed to address the complex challenges facing agriculture and develop and improve the sustainability and resilience of the agri-food system. The most prominent concepts refer to sustainable intensification (Garnett et al. 2013, Pretty 2008, Struik et al. 2014), organic farming (Muller et al. 2017, Niggli 2015b, Seufert & Ramankutty 2017), conservation agriculture (Giller et al. 2009, Hobbs et al. 2008, Knowler & Bradshaw 2007), regenerative agriculture (Francis et al. 1986, LaCanne & Lundgren 2018, Rodale 1983), ecological intensification (Cassman 1999, Tittonell 2014), and agroecology (Altieri 1989, 2002; Francis et al. 2003; Gliessman 2014; Gliessman & Tittonell 2015; Wezel et al. 2009), which partly overlap with each other but have different characteristics (see, e.g., Giller et al. 2021, IDS & IPES-Food 2022, Pretty & Bharucha 2014, Struik et al. 2014, Tittonell et al. 2022).

Agroecology has received increasing attention in recent years (Gliessman 2015) and is considered by its supporters as the ultimate and most comprehensive solution to the many challenges facing the agri-food system (Gliessman & de Wit Montenegro 2021). It is seen as the foundation for transforming the agri-food system and achieving sustainability (Gliessman 2021). Agroecology aims to combine the science on (agro)ecology with agricultural practice and societal interests (Wezel et al. 2020). In fact, it has become a strong societal movement (Gliessman & Ferguson 2020, Wezel et al. 2020). Based on agroecological concepts, principles, and practices, numerous local solutions have been developed with the aim of maintaining long-term productivity and food security, providing ecological benefits, and reducing negative external effects including aspects of injustice and inequality of the currently predominant conventional agricultural practices (Atta-Krah et al. 2021, FAO 2018a, HLPE 2019).

Despite the increasing attention being paid to agroecology and the growing number of successfully developed practical solutions, it remains an important question to what extent and how agroecology can be scaled up to become the main approach for a sustainable and resilient agri-food system (Tittonell 2020). Respective research agendas have been developed (Gascuel-Odoux et al. 2022), but more insights into the economic viability of agroecological practices and possible policy interventions for a wide range of farming systems are needed. The adoption of agroecological practices is voluntary for farmers and other food system actors. Thus, it is relevant to understand adoption hurdles and enabling factors that can be used to largely increase the uptake of agroecological practices.

Most successful current examples of mainstreaming agroecology come from smallholder, family agriculture (Tittonell et al. 2020). Gliessman (2020) estimates that approximately 30% of (mainly small-scale) farms around the world adopted some agroecological practices or redesigned their production systems around agroecological principles. For mainstreaming agroecology, consideration of larger farms is also required and new technological opportunities must be embraced (Tittonell 2020). The importance of new technologies related to digitalization (Asseng & Asche 2019, Basso & Antle 2020, Walter et al. 2017) and breeding (Qaim 2020) is increasingly recognized for agroecology (Bellon-Maurel & Huyghe 2017, Gascuel-Odoux et al. 2022). Moreover, effective agroecological practices, favorable markets, and targeted policies have been identified as key drivers of the process of taking agroecology to scale (Mier y Terán Giménez Cacho et al. 2018). However, the concept of agroecology is not yet widely addressed in agricultural, environmental, and resource economics and policy.[1]

Proponents of agroecology advocate a holistic view and systems approach on agriculture and food security (Gliessman 2018, Wezel et al. 2020). However, systems analysis supported by model simulation and assessment is less evident, and effects of change in climate (Asseng et al. 2015, Rosenzweig et al. 2013), markets (Nelson et al. 2014), management activities (Leip et al. 2008, van Ittersum et al. 2008), policies (Britz & Hertel 2011) or diets (Willett et al. 2020) and related feedbacks are rarely quantified for agroecological systems. A few efforts have been made to quantify the implications of shifting globally from conventional to organic agriculture (De Ponti et al. 2012, Seufert et al. 2012) but to our knowledge this has not yet been done for agroecology at large. At the same time, the lack of support from the agricultural research community and established knowledge systems to support agroecological farming has been articulated (Niggli & Riedel 2020). Embracing the systems approach fully, future agroecology research should include more interdisciplinary and transdisciplinary work and consider multiple entry-points and transition trajectories, including social, cultural, political, and economic issues (Wezel et al. 2020).

The aim of this review is to examine the potential for agroecology to serve as the model for a sustainable and resilient agri-food system (Section 5). We review the literature to understand the current emphasis and future directions in agroecology research. We explore agroecology from different perspectives, including the food system and economic and policy perspectives, and look at the potential role of new and emerging technologies related to digitalization and breeding. We do not aim to compare agroecology with other types of sustainable agriculture, but comparative examples are used, where useful, to highlight specific characteristics of agroecology.

The remainder of this review is structured as follows. Next, we introduce the concept of agroecology in Section 2 and subsequently provide a quantitative assessment of the literature on agroecology (Section 3). In Section 4, we embed agroecology in a food system perspective and investigate possibilities for performance measurement and stakeholder involvement. In this section, we also present insights into the economics and policy of agroecology and present perspectives on the potential of new technologies such as digitalization and new breeding for agroecology. Section 5 provides a synthesis outlining areas of attention required to scale up agroecology and concludes with recommendations for policy action.

2. THE CONCEPT OF AGROECOLOGY

The concept of agroecology is dynamic and has different meanings, often referring alternatively to an inter- or transdisciplinary science, a set of sustainable farming practices, and a social movement (Wezel et al. 2020, Wezel & Soldat 2009). Agroecology has been evolving over many decades (Wezel et al. 2020, Wezel & Soldat 2009). The original research focus was on the ecological study of agricultural systems (Altieri 1995, Dalgaard et al. 2003, Gliessman 2004), mainly related to soil biology and pest management concerns (IDS & IPES-Food 2022) and integrating local knowledge of farmers about ecological processes relevant for managing their agroecosystems (Altieri & Toledo 2011, Gliessman et al. 1981). Stronger consideration of ecological processes implies a paradigm shift away from the focus on productivity-driven conventional farming. For example, utilizing soil biological diversity for plant nutrition may reduce the amount of mineral fertilizer

[1]For example, the term agroecology has not been used in titles of papers published in leading journals in the field of agricultural economics and policy (see Finger et al. 2022 for a journal list).

use and improve resistance against plant diseases (Deguine et al. 2023). Agricultural practices and local solutions and approaches are codeveloped and implemented in close interaction with farmers, considering ecological processes and ecosystem services (Wezel et al. 2014, 2020).

However, the concept of agroecology has been steadily developing to also include the social and economic dimensions of the entire food system and across all actors (Francis et al. 2003) and most recently to consider the integration of research, education, action, and change to all parts of the food system (Gliessman 2018). Accordingly, agroecology is presently defined as "the integration of research, education, action and change that brings sustainability to all parts of the food system: ecological, economic, and social." In addition, "The approach is grounded in ecological thinking where a holistic, systems-level understanding of food system sustainability is required" (Gliessman 2018, p. 599). Key features are that agroecology "is transdisciplinary in that it values all forms of knowledge and experience in food system change," "is participatory, as it requires to involve all stakeholders along the food value chain" (from the farm to the table), and "is action-oriented, as it confronts the economic and political power structures of the current industrial food system with alternative social structures and policy action" (Gliessman 2018, p. 599). The definition of the Food and Agriculture Organization of the United Nations (FAO) that is often used refers to "agroecology as an integrated approach that simultaneously applies ecological and social concepts and principles to the design and management of food and agricultural systems. It seeks to optimize the interactions between plants, animals, humans and the environment while taking into consideration the social aspects that need to be addressed for a sustainable and fair food system" (FAO 2018b, p. 1).

The overall aim of transformation to agroecological practices is to reduce negative external effects in environmental, economic, and social dimensions implied by currently dominating conventional agricultural practices. Agroecology is thus seen as a dynamic and holistic approach to agriculture that combines science, a set of agricultural practices, and a social movement to support the transition of agri-food systems toward more sustainable practices and fairer outcomes. So far, the social movement has been particularly strong in support of small-scale farmers and indigenous people for developing alternatives to industrial agri-food systems. Much emphasis has been on building locally relevant food systems supporting the economic viability of rural areas through safe food production, short marketing chains, and fair trade (Wezel et al. 2020). Beyond adoption by small-scale farmers, agroecological transformation will require a shift away from a mainly capital-oriented approach to a more labor-oriented one strengthening the social relations of production (Niggli et al. 2021, van der Ploeg 2021). The related implications of such shifts for the economic and political system will likely be considerable.

Along these lines, supporters of agroecology envision it as a suitable concept to lead the transformation to more sustainable agri-food systems (Gliessman & de Wit Montenegro 2021). This would range from the local farm to the broader landscape and regional scales and up to the global scale (Dalgaard et al. 2003; Tittonell et al. 2020; Wezel et al. 2009, 2020), including all relevant interactions and feedbacks in a holistic way.

In order to conceptualize agroecology, five levels of agroecological transition have been distinguished (Gliessman 2016) in addition to no agroecological integration (level 0) and related to the agroecosystem (levels 1–3) and food system (levels 4 and 5) as well as to incremental (levels 1 and 2) and transformational (levels 3–5) changes (**Figure 1**). As a result of a multistakeholder process by the FAO, 10 elements of agroecology have been put forward (FAO 2018b) (**Figure 1**). The High Level Panel of Experts on Food Security and Nutrition (HLPE) responded to a request by the UN Committee on World Food Security (CFS) to report on "agroecological approaches and other innovations for sustainable agriculture and food systems that enhance food security and nutrition" and recommends 13 principles of agroecology (HLPE 2019) (**Figure 1**).

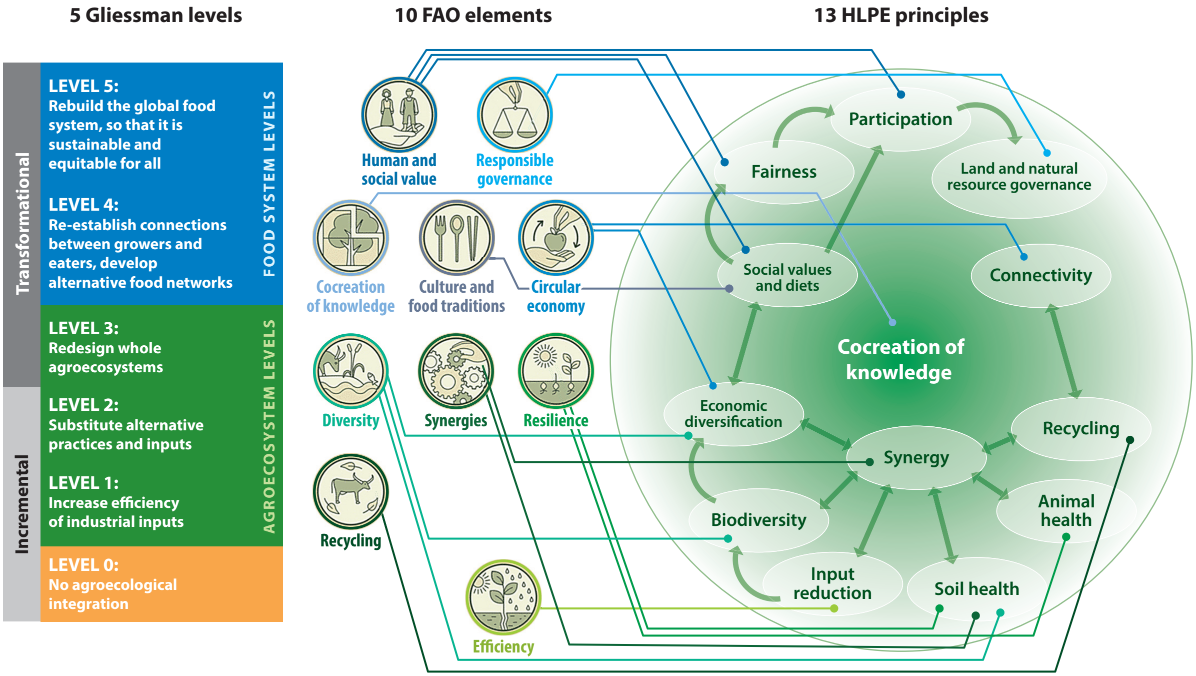


Figure 1

Levels, elements, and principles of agroecology. Note that links between elements and principles are shown through connecting lines, whereas the color of the lines refers to the levels on the graph. Figure adapted with permission from Atta-Krah et al. (2021) and Wezel et al. (2020).

Large international organizations and expert panels have addressed agroecology in strategic documents such as those by the FAO (2014, 2018a,b), the HLPE (2019), or the UN Food Systems Summit 2021 (Niggli et al. 2021) complemented by reports from international and national research organizations (Atta-Krah et al. 2021, Caquet et al. 2020, Snapp et al. 2021) and international projects and programs related to agroecological research.[2] Although there are different perspectives on agroecology, which are elaborated in Section 4.1, there is also a notable convergence of terms and definitions resulting in the formation of these principles, elements, and levels of transition brought forward recently with numerous representative examples on the adoption of agroecological principles across the globe (Atta-Krah et al. 2021, Wezel et al. 2020) (**Figure 1**).

3. AGROECOLOGY IN THE LITERATURE

Aiming to better understand the dynamics of research conducted on agroecology, we provide a quantitative analysis of the peer-reviewed publications findable through the Web of Science under the keywords "agroecology" and "agro-ecology." First, we analyzed temporal changes in the number of articles published in agroecology. Second, we used quantitative approaches to analyze

[2]Also, in preparation for a larger European partnership on agroecology under the EU research framework programme Horizon Europe, input from two Coordination and Support Actions, ALL-Ready (**https://www.all-ready-project.eu/**) and AE4EU (**https://www.ae4eu.eu/**), and the Standing Committee on Agricultural Research (SCAR) have been provided (**https://scar-europe.org/home-scar/news-display/221-agroecology-partnership-s-sria**).

patterns and trends of topics. Third, we generated word clouds based on term frequency to identify the most important terms within the peer-reviewed literature and within recent reports by large international institutions. For the quantitative analysis, we applied the statistical method of latent Dirichlet allocation (LDA) (Blei et al. 2003, Hoffman et al. 2010), which is available as a Python library gensim 4.3.1 (**https://pypi.org/project/gensim/**). The LDA assumes that each document (here: title, abstract, and keywords) consists of a mixture of hidden topics. Within each document, each word is associated with a specific topic. The topic distribution is hidden (latent), and the word distribution is a continuous and multivariate distribution named after Dirichlet. The LDA iteratively draws a distribution of words from the documents and calculates the probability distribution based on the random drawing until the convergence criteria are satisfied. A single document can be grouped into one major general topic or into several more specific subtopics simultaneously. In this review, the LDA was used to identify (*a*) general topics across the corpus and (*b*) more specific but still rather general subtopics.

Based on our analysis, the number of peer-reviewed scientific publications on agroecology has increased considerably in the last two decades, from close to zero to nearly 600 articles per year currently (**Figure 2*a***). Likewise, numbers of publications have also increased for other related

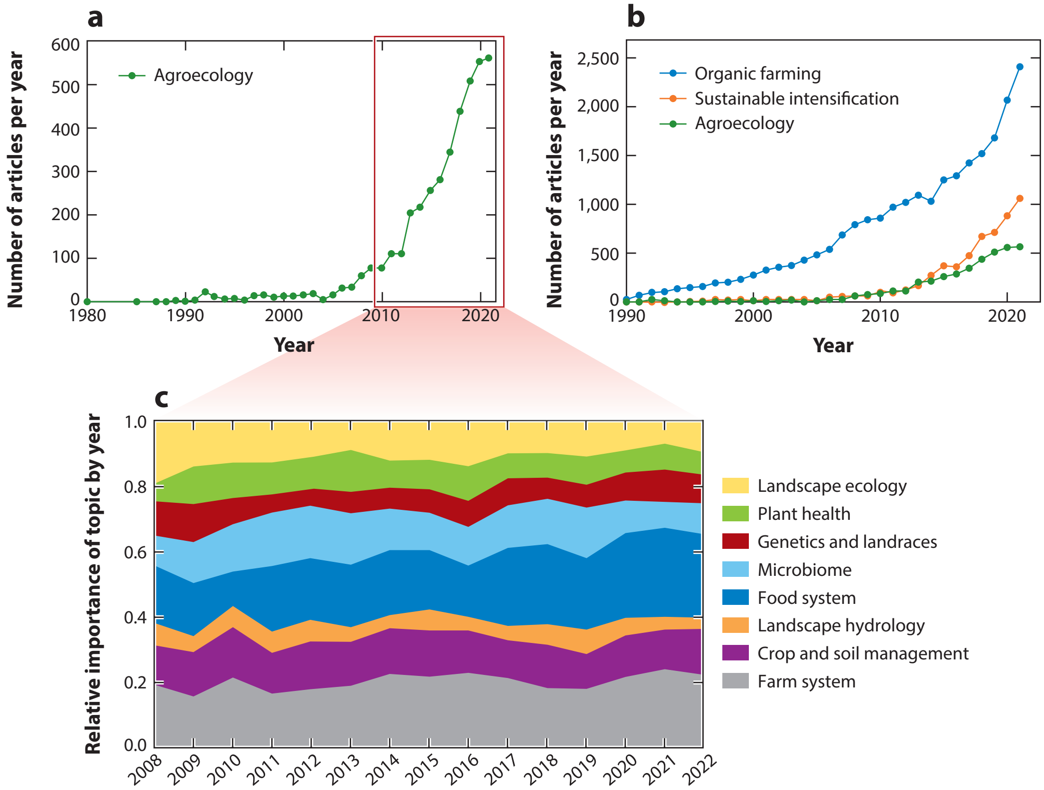


Figure 2

The growing importance of agroecology and underlying subtopics in the peer-reviewed literature found in the Web of Science between 1980 and 2021 using the search string "all fields" for "agroecology OR agro-ecology." (*a*) Number of articles published per year; (*b*) comparison of number of articles published per year on organic farming, sustainable intensification, and agroecology; and (*c*) the annual change in relative importance of the eight distinct agroecological subtopics based on all obtained articles between 2008 and 2022. Data from the Web of Science provided by a license to ETH Zürich and ZALF.

types of sustainable agriculture that overlap with agroecology, such as organic farming or sustainable intensification (**Figure 2*b***). Notably, subtopics have changed over time in their relative contributions to the overall number of articles published on agroecology (**Figure 2*c***). The number of articles focusing on the food system with emphasis on systemic change and food system transitions has been steadily increasing since 2008, which indicates a growing focus on food systems in agroecological research. In contrast, the number of articles on landscape ecology and microbiome has been declining in relative terms over the same period (**Figure 2*c***).

Analyzing the clustering of topics and subtopics and relationships among these reveals that the eight identified subtopics cluster into the two main topics "agri-food system" and "crop-soil system," with little overlap among these groups, as visualized by the Sankey diagram (**Figure 3*a***). On the one hand, articles on the "agri-food system" mainly address subtopics, which have a stronger

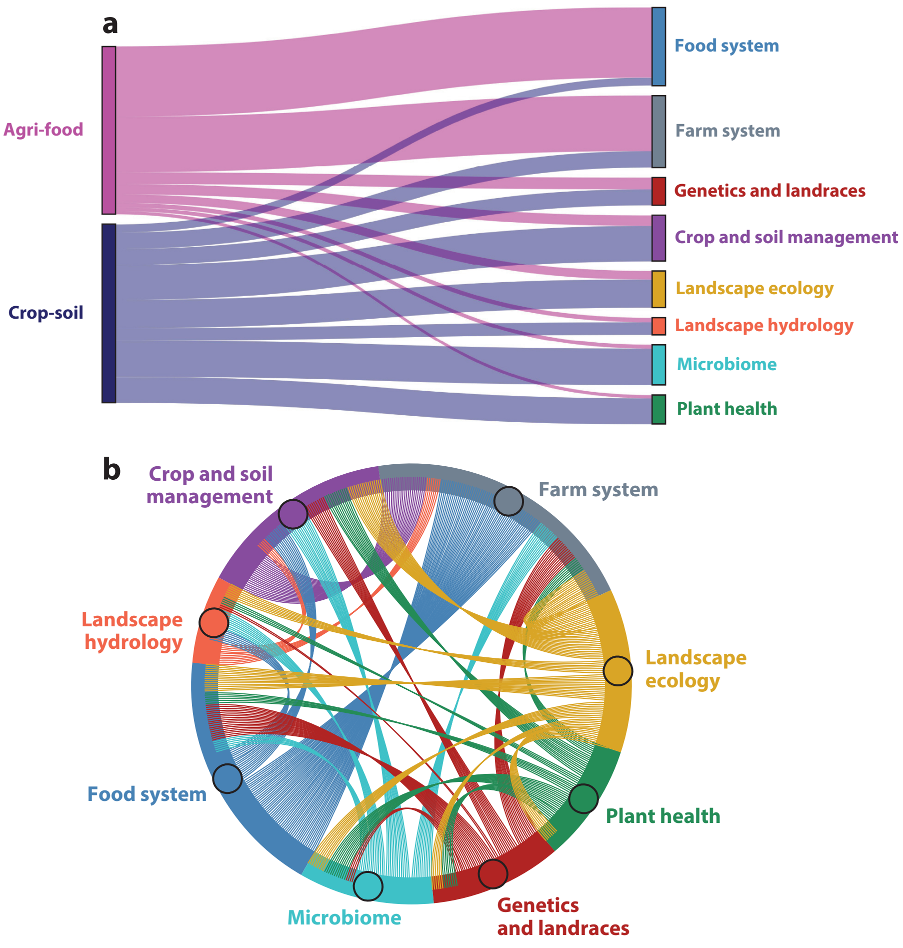


Figure 3

Topics and subtopics of agroecology in the peer-reviewed literature found in the Web of Science. (*a*) Sankey diagram visualizing how articles assigned to eight subtopics relate to the two general major topics, the agri-food system and crop-soil system. (*b*) The inner product of shared subtopic distributions by document, visualizing the relationships among the eight subtopics. Data from the Web of Science provided by a license to ETH Zürich and ZALF.

food and farm system perspective, more emphasis on system transitions and socioeconomic aspects, and less emphasis on agronomic, crop, and soil science–related subtopics. On the other hand, articles on the "crop-soil system" relate to subtopics with a stronger environmental research focus (**Figure 3*a***) and barely address aspects of the food system or system transition. Relationships among subtopics support this observation (**Figure 3*b***). Strong relationships were found between the two subtopics "food system" and "farm system" and "crop and soil management" and "farm system." Many smaller subtopics such as "landscape ecology" or "genetics and landrace" were evenly interconnected with other subtopics but without particularly strong connection (**Figure 3*b***). The segregation into subtopics with and without system relevance demonstrates which other research topics contribute to farm and food systems research despite being individual research topics. Research topics such as plant health and microbiome play a lesser role than does food and farm systems research.

Hence, our analysis reveals that there are few, if any, articles that offer a comprehensive system approach including all aspects of agroecological research from plant health to food systems (**Figure 3**). This is also evident from a comparison with recent reports by large international organizations (Atta-Krah et al. 2021; FAO 2014, 2018b), which represent an additional large body of literature on agroecology often not published in peer-reviewed journals. Across the whole corpus of peer-reviewed articles in the Web of Science, the most important terms used are "soil," "system," "crop," "food," "production," and "increase," which are similar to those in the reports analyzed in **Figure 4**. The frequency of other terms addressed in this literature review, such as "policy, "markets," "innovation," and "technology," reaches roughly 10% relative to the most frequent terms (**Figure 4**).

4. PERSPECTIVES ON AGROECOLOGY AND PATHWAYS FOR LARGE-SCALE ADOPTION

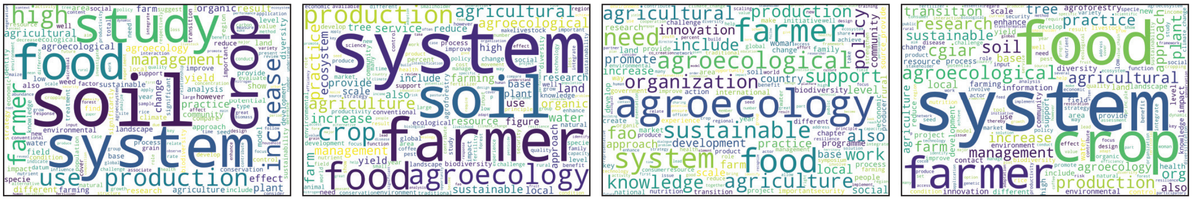
4.1. Food System Perspective

The concept of agroecology aims to embrace the whole food system. However, references to advance agricultural and food systems research interactively with the food system research community are often lacking. Hence, an explicit effort is made to understand the (agri-food) system concept of agroecology in conjunction with concepts and approaches typically used in the agricultural and food systems science domain.

4.1.1. System concept. While the concept of agroecology has continuously shifted its system boundaries to include larger organizational structures (from fields and farms to the overall food system) as well as spatial (local to global) and temporal (within season to decadal) scales, the resulting complexity has prompted the need to consider more drivers (environmental, economic, policy, and sociocultural) along with additional impacts and perspectives within a more holistic food system approach. These different perspectives on the complex agri-food system, including transformation, which agroecology aims to integrate, mainly refer to (*a*) the three dimensions of sustainability (environmental, economic, social), (*b*) the UN's Sustainable Development Goals (SDGs), (*c*) levels of organization (from field to farm and regional to global), (*d*) relevant actors and stakeholders, (*e*) food value chain components, (*f*) codesign processes, and (*g*) activities (**Figure 5*a***).

Although a systems approach is advocated by agroecology, it is not always clear how this relates to the system concept of agricultural and food sciences. Briefly, the application of system science to agriculture (de Wit 1968, Leffelar 1998) has been used to conceptualize, analyze, and assess agricultural and associated problems of sustainability and sustainable development for European

a Web of Science (1980–2021) **b** FAO (2014) **c** FAO (2018b) **d** Atta-Krah et al. (2021)



a Web of Science (1980–2021)

Important terms	F
Soil	5,768
System	5,230
Crop	3,712
Study	3,629
Food	3,392
Production	2,937
Increase	2,907
Selected other terms	
Policy	740
Market	488
Economic	819
Innovation	413
Technology	403
Digitalization	7
Breeding	353
Genetic	495

b FAO (2014)

Important terms	F
System	1,195
Farmer	761
Soil	732
Food	657
Agroecology	522
Production	490
Crop	474
Selected other terms	
Policy	148
Market	152
Economic	142
Innovation	66
Technology	117
Digitalization	0
Breeding	24
Genetic	34

c FAO (2018b)

Important terms	F
Agroecology	1,191
Food	796
Farmer	725
System	568
Need	382
Agroecological	374
Sustainable	352
Selected other terms	
Policy	293
Market	143
Economic	146
Innovation	255
Technology	91
Digitalization	1
Breeding	9
Genetic	10

d Atta-Krah et al. (2021)

Important terms	F
System	587
Food	379
Crop	325
Farmer	294
Agroecological	288
Soil	239
Production	227
Selected other terms	
Policy	65
Market	76
Economic	56
Innovation	114
Technology	44
Digitalization	1
Breeding	28
Genetic	43

Figure 4

Word clouds showing the relative importance of terms in agroecological publications. Listed terms show the most important terms and selected terms addressed in these studies measured by the relative frequency (F) of their occurrence in (*a*) articles (titles, abstracts, and keywords) published in the Web of Science, (*b*) *Proceedings of the FAO International Symposium* (FAO 2014), (*c*) *Proceedings of the Second FAO International Symposium* (FAO 2018a), and (*d*) *Agroecological Transformation for Sustainable Food Systems* (Atta-Krah et al. 2021). Cited sources are for data only.

(Ewert et al. 2009, van Ittersum et al. 2008) and global agriculture (Rosenzweig et al. 2013) across various levels of organization (Ewert et al. 2011).

Moving beyond a production-oriented perspective on food security (Ingram et al. 2008), the agri-food system approach considers agriculture as an integral part of the food system (Clark et al. 2018, HLPE 2017, Ingram 2011, Springmann et al. 2018, Willett et al. 2020). Many efforts have been made to apply the systems approach and conceptualize the food system considering drivers, activities, and outcomes (Ericksen 2008, Ingram 2011). An even more elaborate conceptualization of the food system has been proposed by the HLPE (2017) that considers drivers and impacts, but also actors, food environment, consumer behavior, diets, and political and institutional action (**Figure 5*b***). The importance of considering levels of organization and respective spatiotemporal scales has recently been highlighted (Hertel et al. 2021, von Braun et al. 2021) (**Figure 6**). von Braun et al. (2021) also stated that a practical definition of food systems should meet two essential criteria: (*a*) suitability for the purpose at hand guiding not only scientific questions but also action and (*b*) sufficient precision to define the domains for policy and programmatic priorities but not exclude larger ambitions such as the dimensions of sustainability. Here, the risk of intellectual bias toward overly complex mappings of the food system has been noted. At the same time, analyses of food system behavior and change can be too narrow (von Braun et al. 2021) owing to the limitations of available operationalized models and tools (Ewert et al. 2015).

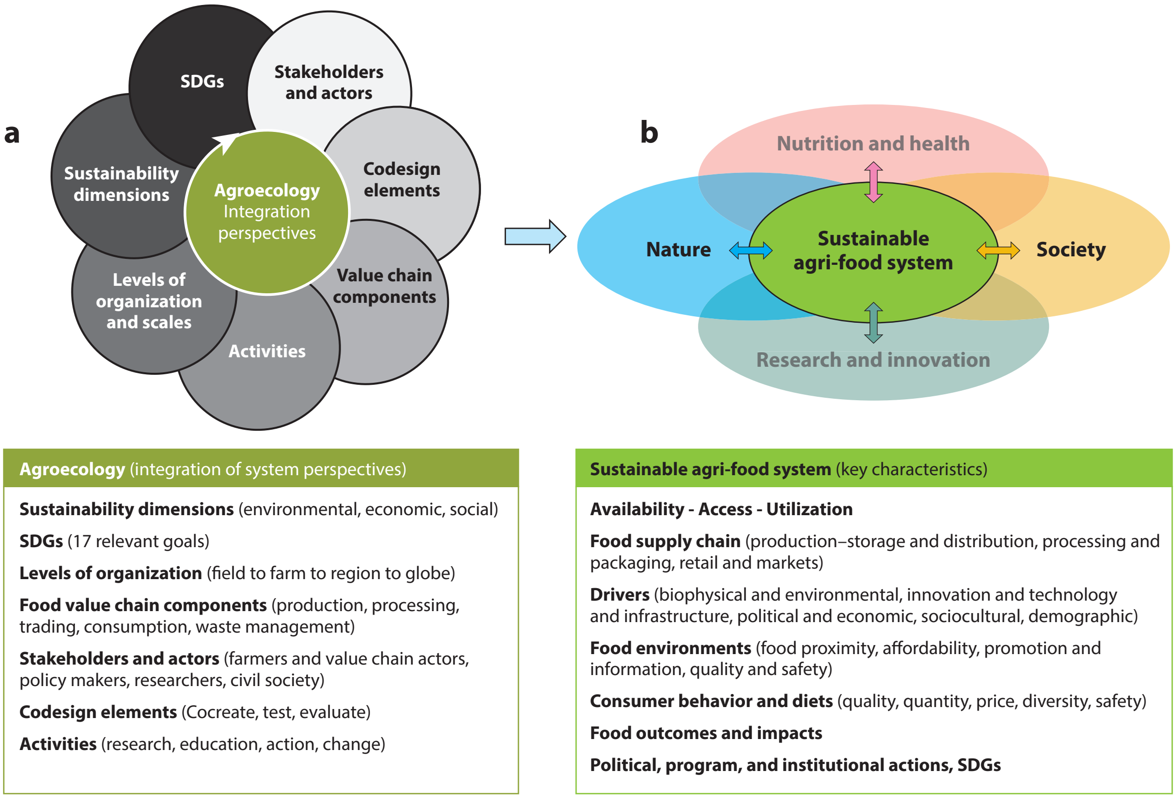


Figure 5

The concepts of agroecology and the sustainable agri-food system. (*a*) Agroecology aiming to integrate aspects of the food system from different viewpoints and (*b*) the sustainable agri-food system with its interrelated key characteristics (HLPE 2017) and important surrounding systems. Cited source is for data only.

Hence, the conceptual delineation of the agri-food system investigated, including identification of important characteristics, relationships among them, and interactions with related systems, will need to be determined in a context-specific way based on the specific problem to be addressed (Ewert et al. 2009). This initial step is important for further analysis and assessment of system performance and change. It will also help to identify important drivers and indicators (**Figure 6**) as well as the applied tools, data, and models for assessment. Engagement with key stakeholders is important for all steps. Links between local and global system elements and respective drivers and impacts need particular attention for agroecology to overcome segregation into topical research clusters (see Section 3).

4.1.2. Measuring and evaluating agri-food systems. The agri-food system concept includes approaches to assess the performance and change of these systems as well as trade-offs and synergies. Much work has been done to develop integrated assessment frameworks for the agri-food system, but these are not reviewed here (see Antle et al. 2017, Ewert et al. 2009, Muller et al. 2020, Rosenzweig et al. 2013, van Ittersum et al. 2008). Due to the complexity of relationships and processes, models are typically used to utilize the scientific evidence of the important relationships and interactions captured by these models. Although model capabilities to capture the complexity of the agri-food system are still limited (Ewert et al. 2015, von Braun et al. 2021), some models

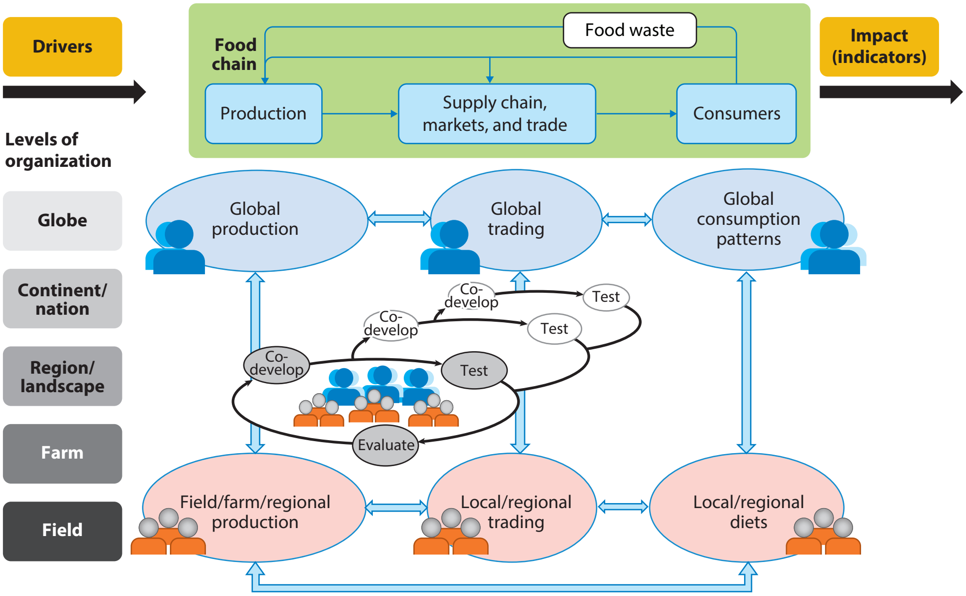


Figure 6

Food value chain with drivers and impacts and local to global interactions considering multiscale actors and stakeholders in a codesign approach for codevelopment, testing, and evaluations of sustainable agri-food systems across levels of organization. Note that agroecology thus far has a strong emphasis on local and regional solutions.

have already made substantial contributions to our understanding of parts of the agri-food system and their sensitivity to changes in selected drivers. For example, climate change impacts on crops were quantified using crop growth models and climate change projections (Asseng et al. 2015, Zhao et al. 2017). By 2050, global economic models coupled to crop growth simulations predict an impact from climate change on agricultural markets, a decline in total crop yield of 11%, and a rise in producer prices by 20% (Nelson et al. 2014). Moreover, trade-offs such as those between production and biodiversity (Seppelt et al. 2021) and policy analysis (Reidsma et al. 2018) have been conceptualized and evaluated.

In agroecology, only few modeling studies have become available. In a recent study on food security, key factors of the farm system accounted for 85% of the variation in food security for several of more than 5,000 farms using an artificial neural network (Benítez et al. 2022). Classical crop model–based impact assessment studies have been provided for selected crops (Doi et al. 2020). A predictive artificial neural network for food security has been used to identify the most important factors and their relationships to food security and to account for 85% of variability in food security (Barba-Escoto et al. 2020). Cognitive maps have been employed to incorporate views and perceptions from actors across multiple social sectors for better-informed decision making regarding problems such as soil degradation (Arroyo-Lambaer et al. 2021). Models have also been used to explore the transition to agroecological systems (Ong & Liao 2020) and the complexity of agroecology (Vandermeer 2020).

Based on an earlier review by Mottet et al. (2020), a comprehensive tool for agroecology performance evaluation (TAPE) was developed with contributions by 70 representatives of agroecology-related organizations worldwide. In this approach, four steps are distinguished: Step 0 is a description of the main agri-food systems characteristics (socioeconomic and demographic) and drivers (policy, market, technology, sociocultural, and/or historical drivers); step 1 is the characterization of agroecological transitions, based on *The 10 Elements of Agroecology* adopted by the FAO (FAO 2018b) and its member countries (**Figure 1**) assessing the degree of transition based on a descriptive scale using scores with information from the farm/household and community/territory scale; step 2 includes the core criteria of performance using indicators relevant to address the respective SDGs; and step 3 is a participatory validation of the results obtained from the previous steps with the producers and relevant stakeholders.

Indicators are crucial for assessing system change. Comprehensive indicator frameworks have been developed to measure important features of the agri-food system with respect to the implications for systems in transition (Alkan Olsson et al. 2009, Mouratiadou et al. 2021). System performance assessments should be based on indicators that measure to what extent the impact of driver(s) on the system is or is not sustainable (Mouratiadou et al. 2021) (**Figure 6**). Here, 37 themes, 142 subthemes, and 1,128 metrics were identified to measure and evaluate indicators for sustainable intensification options. For an increasing number of indicators, a good scientific basis about their preferred targets (or ranges) is available, e.g., for nitrate leaching, greenhouse gas emissions, climate-neutral agriculture, or farmers' income. In addition, an increasing number of these indicators can be modeled and/or monitored. Importantly, digital solutions can be vital to overcome current limitations (see Section 4.2.3).

4.1.3. Involvement of actors and stakeholders. In agroecology, relevant actors and stakeholders are closely involved in the development and evaluations of the respective systems (Mottet et al. 2020). From an agri-food system perspective, complex mappings and analyses of actors and stakeholders and their roles have been performed (Doernberg et al. 2016, Gascuel-Odoux et al. 2022, Schulp et al. 2022). Importantly, most of these analyses have been performed at local and regional scale, with relatively few applied at global scale. Recently, the Group of Chief Scientific Advisors of the European Commission has announced that success in transitioning to sustainable food systems will require bringing together the European, national, regional and local stakeholders in the food system (Eur. Comm. 2020) (**Figure 6**).

The proposed participatory approaches will be challenging because stakeholder groups will be required to interact across organizational levels and likely represent quite different interest groups and aims. A promising approach to cope with this is the development of living labs (Folstad 2008, Steen & van Bueren 2017) that can be implemented at landscape and regional levels. Living labs consider the central role of the user and involve all relevant actors and stakeholders within a local or regional system. Living labs draw on the concept of cocreation of sustainable solutions for the respective system (Steen & van Bueren 2017, figure 8). An example of local implementation of the living lab concept is provided by the network of agroecosystem living labs in Canada (McPhee et al. 2021). An important element of the living lab approach can be on-farm experimentation (Lacoste et al. 2022). However, for large-scale adoption, the living lab approach will also require the involvement of large-scale actors such as big corporations and governments related to important drivers of change (economics, policy, and technology) (**Figure 6**).

4.2. Perspective on Drivers of Large-Scale Adoption

The literature review in Section 3 has revealed that topics that we find important for understanding the potential for widespread adoption of agroecology have received relatively little attention in the literature so far. In particular, aspects of economics and agricultural policies and the role of new and emerging technologies are critically important in this regard and have therefore been specifically addressed in this article.

4.2.1. Economics of agroecology. Economic, social, and other implications of agroecology range from the level of the field to farm and to regional, national, and global levels. Decision making toward agroecology spans farm households to industry and consumers (**Figure 6**).

However, a key requirement for the broader use of agroecology globally remains, which is that farmers take up agroecological practices. We therefore take the level of the farm as a crucial starting point and embed discussions on the role of markets and different market actors in enabling the adoption and diffusion of agroecology.

A wide range of possible determinants explains why farmers take up or fail to take up new production practices and systems as is required to achieve agroecological transformation. For example, farmers' motives, values, perceptions, preferences, and personalities come into play when deciding whether to alter current farming practices (Dessart et al. 2019). However, the implications for farm and household incomes are also relevant. Farms need to maintain economic viability to ensure long-term survival (Finger & El Benni 2021). Grovermann et al. (2021, p. 1001) state: "To work for farmers, it [agroecology] needs to make economic sense..." Indeed, agroecology is often assumed to increase value-added and profitability (D'Annolfo et al. 2017, van der Ploeg 2021, van der Ploeg et al. 2019).

Farms adopt agroecological practices (see Section 2) if the change in expected utility induced by this adoption compared to current conventional farming practices is positive (Mohring & Finger 2022). One key element is the expected change in profitability. Changes in perceived profits due to the adoption of agroecological practices can be caused by changes in several components such as yields, prices, costs, and governmental support. In the short run, switching to low-input production systems and production without or with reduced pesticide use, may imply lower yields (van der Ploeg et al. 2019). However, switching to agroecological practices may enable producers to generate higher producer prices (e.g., via labeling or by creating new marketing channels). Agroecological production also implies changes in production costs. For example, a lower reliance on external inputs (e.g., fewer pesticides and artificial fertilizer) implies that expenditures for external inputs are also reduced, and this may imply increases in the ratio of value-added and the gross value of production (van der Ploeg et al. 2019). However, the relevance of different factors remains very farm and context specific. For example, De Leijster et al. (2020) find for a case study of almond production in Spain that the long-term profitability of agroecological farming practices was best explained by differences in yields, not operational costs. However, adoption of agroecological practices can require changes in the required quantity and quality of labor (van der Ploeg et al. 2019). For example, switches away from chemical pest management strategies are often associated with higher labor demand. The availability and costs of labor thus remain critical factors. Finally, in some countries, the adoption of specific agroecological practices is compensated with additional governmental support (e.g., direct payments) (see Section 4.2.2).

A switch to agroecological practices may also induce a change in perceived income risks. Reducing external inputs (e.g., lesser reliance on pesticides) often results in higher perceived production risks. For example, organic farming is often found to be more risky (i.e., facing a more volatile income) than conventional farming practices (Iyer et al. 2020, Serra et al. 2008). However, agroecological farms are often more diversified, e.g., by relying on a broader set of farm activities (e.g., integrating crop and livestock production) and income sources. This reduces income risks and increases resilience. Agroecology often also relies on more diverse production systems (e.g., with higher species richness) that often imply lower yield risks and can induce long-term stability of production and profits (Di Falco & Chavas 2009, Schaub et al. 2020). In a review on agroecology and climate change supported by the Consultative Group on International Agricultural Research (CGIAR) and its research program on Climate Change, Agriculture and Food Security (CCAFS), good evidence was found for the impacts of farm diversification on climate change adaptation (Snapp et al. 2021). Moreover, agroecology enables new alliances between producers and consumers that can imply more stable market environments and thus lower price risks.

The economic implications for profits, input demand, and the risks of switching to agroecological practices critically depend on structural characteristics of both farms and farmers, such as the endowments of the farm with land and labor resources as well as the focus of the farm (e.g., arable versus mixed production systems). Moreover, switching production systems always induces farm-specific adjustment costs caused by required changes in knowledge, farm structures, and capital goods (Gardebroek & Lansink 2004). These adjustment costs can be reduced by tapping into the cooperative character of agroecology, e.g., by reducing learning costs and sharing technology. For example, Marton & Storm (2021) find positive spatial spillover effects for the adoption of organic farming in Norway. Colearning and living lab approaches (see Section 4.1.3 and **Figure 6**) can be supportive in this regard.

In addition, various behavioral factors are key for farmers' decisions to adopt agroecological production practices. This comprises, for example, farmers' risk and time preferences (Iyer et al. 2020). Moreover, Dessart et al. (2019) show that further behavioral factors, e.g., dispositional, social, and cognitive factors, explain farmers' uptake of sustainable production practices. Especially given the characteristics of agroecology (e.g., also being a movement), we expect that farmers' personalities, motives, values, and social interactions are key elements for the adoption of agroecology, assuming that a minimum economic viability is ensured (see Dessart et al. 2019). This implies that the profitability of agroecological practices at the farm level is only a necessary but not a sufficient condition for its uptake. Moreover, to broaden the use of agroecology, incentive mechanisms need to account for the heterogeneity of farms and farmers, e.g., their behavioral characteristics.

Several studies synthesize evidence on the overall economic implications of agroecology at the farm level. For example, van der Ploeg et al. (2019) present a series of illustrative examples from European agriculture where organic and/or low-input farming systems have been found to be more economically viable. For example, they show that for a sample of 354 conventional and 170 agroecological grassland-based farming systems in France, the value-added for every €100 produced was ca. 50% higher for agroecological farms compared to conventional farms. Such a positive effect has also been identified for other regions of the world (Bolwig et al. 2009, Mendoza 2004). D'Annolfo et al. (2017) also show that adoption of agroecological practices resulted in higher profits in two-thirds ($N = 73$) of the reviewed studies with global coverage. Grovermann et al. (2021) study the economic viability of organic dairy farming across 25 European countries using farm accountancy data from 41,903 dairy farm enterprise observations. They found that organic production is associated with higher gross margins for dairy farms (in the range of €66–234 per cow).

A key open aspect in the literature remains the rigorous identification of the economic (as well as social and environmental) effects of the adoption of agroecological practices. Existing assessments rarely account for possible biases, e.g., due to selected or omitted variables (see, e.g., Grovermann et al. 2021 for an exception). For example, farms currently adopting agroecological practices may be characterized by systematic differences in resource endowments and skills (e.g., larger farms and better educated farmers) that would allow them to generate higher profits and yields than other farms, even in the absence of agroecology. Establishing required causal relationships to guide decision making requires appropriate econometric or experimental research designs (Wuepper & Finger 2023). Moreover, the economic implications of the widespread use of agroecology (vis-à-vis being adopted only by few) need still to be identified.

Creating markets that are favorable to agroecology will be necessary to broaden the use of agroecology and can contribute to ensuring long-term economic viability for many farmers and other food system actors. For example, organic producer and related certification is often characterized by higher prices (Grovermann et al. 2021, Ssebunya et al. 2019), but nonorganic production schemes can also be compensated with higher prices. Mohring & Finger (2022) report that low-pesticide and pesticide-free, but nonorganic, crop production in Switzerland is compensated with higher prices. However, the capacity of markets to enable such price markups (whether certified or not) is often limited (Munoz et al. 2021). For example, Bottazzi & Boillat (2021) report that only a small share of the population in Senegal can afford the large price markups for organic food so that organic production generating price markups for producers remains a niche market. Thus, to overcome limited market access, alternative food networks can be created, e.g., by building food citizenship through the participation of producers and consumers and building reciprocal arrangements such as solidarity networks (Mier y Terán Giménez Cacho et al. 2018, Vicente-Vicente et al. 2021). To broaden the widespread use of agroecology globally, however, a better integration in traditional markets must be achieved, e.g., using certification schemes (as proven relevant for organic or fair-trade production) (Mier y Terán Giménez Cacho et al. 2018).

4.2.2. Agroecology in agricultural policies. To broaden the use of agroecology, its concepts and approaches need to be translated and implemented in governmental thinking and finally in actual policies. Agroecology is represented by inclusive innovation technologies that aim to find solutions that are appropriate in the regional and local context (Pereira et al. 2018). Thus, new policy measures may also be needed. In contrast to the support or regulation of specific production methods and technologies, a policy framework and process are needed to develop, enable, and support solutions that are locally appropriate.

However, because agroecology aims to reduce the negative external effects of current agricultural practices (e.g., due to reduced input use), contribute to the provision of ecosystem services (e.g., improved resource use efficiency and soil quality, reduced erosion and greenhouse gas emission, and increased yields and stability), and enhance biodiversity, it already benefits from currently existing policy measures, even without being explicitly mentioned. For example, payments for participation in agri-environmental schemes aiming to reduce pesticide use or increase the uptake of organic farming as well as payments for ecosystem services can incentivize farmers to adopt agroecological practices (De Leijster et al. 2020).

In recent years, agroecology has become increasingly institutionalized (Doré & Bellon 2019) and promoted by international organizations [e.g., FAO, International Federation of Organic Agriculture Movements (IFOAM)–Organics International]. Thus, it is also an essential element of international policy agreements (Loconto & Fouilleux 2019). The long-term implications of these steps still need to be revealed and emphasize the need for respective monitoring and assessment (see Section 4.1.2).

Policies to support agroecology can range from being producer-oriented, consumer-oriented, and market-/trade-oriented, or they may be oriented toward creating an enabling environment representing cross-cutting approaches (see, e.g., Place et al. 2022 for examples and reviews). Although only a few countries have integrated an orchestrated, broad, and significant policy shift in all of these dimensions, various countries have started addressing agroecology in recent policy steps (e.g., Lampkin et al. 2020, Place et al. 2022).

Agroecology is of increasing relevance in European policies. For instance, in France, agroecology is a crucial element in policy documents, e.g., in reference to organic farming and agroforestry and the reduction of phytosanitary products (Lampkin et al. 2020). Moreover, policies were introduced, enabling the explicit promotion of collective action. In the United Kingdom, there has been increasing discussion of agroecological perspectives as part of the debate over leaving the

European Union. Yet, there was only limited recognition in the agriculture bill debated in the UK Parliament in 2020 (Lampkin et al. 2020).

Lampkin et al. (2020) state that Germany is actively promoting organic agricultural practices. Indeed, the formulated goals for the expansion of organic agriculture in Germany go beyond the EU goals (i.e., 30% instead of 25%, as formulated by the European Union by 2030). Beyond the promotion of organic farming, agroecology is increasingly employed in German agricultural policy. An example is a position paper published by 59 organizations (INKOTA 2019) calling for agroecological farming and a commitment to implementing agroecological principles in agricultural policy (Lampkin et al. 2020).

In Switzerland, the government placed agroecology in their research concept for agriculture and food in 2021–2024. It states that agroecology is a pathway to transform today's agricultural and food systems in accordance with the SDGs (BLW 2020). In its report on future directions of agricultural policy, the Swiss government explicitly refers to agroecology, its principals, and its holistic approach (Bundesrat 2022). Thus, future developments of agricultural policy in Switzerland will be guided by agroecology, but the actual implementation steps still need to be established.

In contrast, agroecology is currently of lesser relevance to agricultural policies in Canada (Isaac et al. 2018) and the United States (Miles et al. 2017). Clapp (2021) reports that only a small share of public sector agricultural spending in the United States is currently directed to agroecology initiatives.

More prominently, agroecology is considered as a key concept and opportunity for policies in developing countries.[3] For example, Pereira et al. (2018) argue that developing countries in particular present opportunities to showcase alternative pathways for agricultural development that ensure environmental and social sustainability and ethical responsibility. Agroecology is the "legitimate innovation pathway within agricultural research systems that is more sustainable" (Pereira et al. 2018, p. 9). Yet, Gliessman (2020) states that most governments in developing countries do not foster agroecology sufficiently.

To broaden the use of agroecology in development contexts, public investment in agroecological research but especially the policy environment that enables the development and support of agroecology is suggested. However, Gliessman (2020) reports that, for example, only a fraction of agricultural research funding in Africa is being used for agroecology. He reports that 13% of projects by Kenyan research institutes are agroecological. Along these lines, Bottazzi & Boillat (2021) state that the dynamic advocacy for agroecology in Sub-Saharan Africa so far has had little influence on public policy, and large-scale success of agroecology is still limited. However, the authors also show that there are emerging developments, such as alternative food networks in Senegal, that open up new opportunities for agroecological transformations. These networks, often created by nongovernmental organizations (NGOs), for example, establish cooperatives to purchase products from farmers and distribute them to special marketplaces. In general, the promotion of agroecology in many developing countries is facilitated by intermediary organizations. For example, Iyabano et al. (2022) show that farmers' organizations in Burkina Faso act as intermediary actors to support farmers' adoption of agroecological innovation processes.

There are also important policy developments elsewhere in the Global South. For example, Coq et al. (2020) and Pereira et al. (2018) show that, in Latin America, agroecology is driven by

[3] Note that there are also critical perspectives on major policies aimed at agroecology. For example, Mugwanya (2019, p. 113) claims that the narrow concepts are often too restrictive to meet the transformational need of, for example, African agriculture. The author makes particular reference to the observation of an "anticorporate, anti-industrial sentiment informing the arguments of agroecology."

social movements that have promoted the integration of agroecology into public policies. They conclude, however, that the few implemented policies remain fragile, and a broader support from farmers, consumers, and policy makers is needed. Place et al. (2022) provide other policy examples in Indonesia, Chile, Nicaragua, and India.

Development policies often are a key leverage point toward long-term sustainable transitions of agri-food systems globally, such as by financing the research and implementation of agroecology (Dethier & Effenberger 2012). For example, Gliessman (2020) reports that more than 50% of Swiss-funded projects in Africa have agroecological components. Furthermore, international trade policies can offer opportunities to increase sustainability (Baylis et al. 2021). De Schutter (2011) and Fakhri (2021) also discuss trade and agroecology.

During the recent UN Food Systems Summit 2021 (**https://www.un.org/en/food-systems-summit**), the importance of agroecology and food affordability in the Global South was intensively discussed. The need for urgent and coherent action was emphasized to ensure healthy diets and sustainably produced, safe food for all, and new coalitions such as the School Meals Coalition and the Healthy Diets Coalition were announced.[4] As for agroecology, limited representation has been criticized (IDS & IPES-Food 2022), and several regional and international organizations, mainly NGOs, aiming to represent marginalized rural groups of the Global South organized the Global People's Summit on Food Systems in 2021. Among other concerns, the summit addressed the control of the global food system by powerful nations and big corporations. This shows the huge challenges in integrating food system–related activities, including actors and policies from local/regional scales to international/global scales.

Clearly, agroecology has been adopted by international organizations and international policy agreements and introduced in various national policies, ranging from producer- or consumer-oriented policies to larger-scale (e.g., market-oriented) policies. However, coherent and large policy shifts as well as multinational policy frameworks are still rare. Along these lines, new policy approaches that acknowledge the principles of agroecology, e.g., those that allow stakeholders to develop and support solutions that are locally appropriate, are not yet widely implemented. It remains unclear how much existing policy instruments focusing on more sustainable (economically, socially and environmentally) and resilient agriculture can be adjusted to support agroecology, and to what extent novel policy instruments dedicated explicitly to agroecology are needed.

4.2.3. Agroecology and new and emerging technologies. A wide range of new approaches, production systems, and technologies may contribute to more sustainable and resilient agri-food systems (Pretty et al. 2018, Rose & Chilvers 2018, von Braun et al. 2021). These approaches could also support the widespread adoption and diffusion of agroecological principals and approaches but are rarely considered in the agroecological literature as a viable part of the solutions.

4.2.3.1. Digital technologies. Digital technologies (e.g., remote and proximal sensing, artificial intelligence methods of data analysis, modeling and robotics) are increasingly seen to be part of a fourth revolution of agriculture (Walter et al. 2017). Smart farming technologies can enable higher efficiency of input use (e.g., by using inputs such as fertilizer and pesticides in more targeted ways), better animal welfare, and increased profits for farmers and along the value chain (Basso & Antle 2020, Finger et al. 2019). Digital technologies can also contribute to redesigning agricultural landscapes and systems for sustainability (Basso 2021, Basso & Antle 2020, Walter

[4]New coalitions were announced at the UN Food Systems Summit 2021 to increase access to healthy diets from sustainable food systems (**https://www.who.int/news/item/23-09-2021-new-coalitions-announced-at-the-un-food-systems-summit-to-increase-access-to-healthy-diets-from-sustainable-food-systems**).

et al. 2017). Providing data-driven insights from multiple data sources (sensing and model forecasting) in the inherent variability of agricultural production systems (e.g., regarding climate, soil, topography, and pest damage) allows policy makers to improve decisions on land allocation, production practices, technology use, crop variety choice, and input use at various levels, from the field to the farm and from the landscape to regional scale. Thus, land allocation and production decisions can be tailored to fundamentally redesign agricultural systems so that the root causes of problems are avoided (Gliessman 2016) and critical inputs such as pesticides are reduced. The use of digital technologies can improve crop diversification, biodiversity, and other ecosystem services, often summarized as precision conservation (Basso 2021, Basso & Antle 2020, Northrup et al. 2021). For example, digital technologies can support farmers to design cropping systems in new field arrangements (Donat et al. 2022, Hernández-Ochoa et al. 2022) and allocate resources in a way that production and biodiversity outcomes are optimized at the same time, implementing a high-resolution land sparing concept (Basso 2021).

Digital technologies can also enable improved exchange among farmers, extension services, authorities, and other upstream and downstream actors in the food system (Ehlers et al. 2021, 2022; Finger et al. 2019; Walter et al. 2017). Digital technologies can thus contribute to supporting transformation in food system levels (**Figures 1** and **6**).

Yet, the great potential of digital technologies for agroecology is largely underexploited and sometimes even considered to be controversial (Bellon-Maurel & Huyghe 2017). For example, Ditzler & Driessen (2022) claim that automating agroecology is possible by using advances in agricultural robotics. Along these lines, Pappalardo & Andrade (2022) illustrate the role of low-cost and open-source drone applications for agroecology and organic farming in improving both the efficiency of agroecosystems and the empowerment of local farmers. A more connected agriculture can also be seen as an opportunity to promote agroecological agriculture by providing technologies to better implement, share, and distribute it.

Leveau et al. (2019) present various examples of how digital technologies could be used to support agroecological practices, including digital pest prevention strategies, new tools to facilitate biodiversity improvements, and knowledge exchange and learning platforms. Bellon-Maurel & Huyghe (2017) show that digital technologies contribute through various levers to the agroecological transition because they allow efficacy, substitution, and redesign, e.g., by helping the farmer to achieve flow loop closing and take advantage of biodiversity. Beyond their use in farm agroecology, digital technologies can contribute to reestablishing connections between producers and consumers as well as enable and strengthen global networks across the entire food system and its actors (Walter et al. 2017).

Key areas of conflict and tension in the use of digital technologies might arise from the market power possibly associated with new technologies. For example, who owns the data, who makes decisions, and who has the locus of discretion in a digital agricultural system? These are key questions that must be addressed (Ehlers et al. 2021, 2022; Walter et al. 2017). Moreover, there might be fundamental mismatches between digitalization and agroecology, for example, because digital technologies could imply increases in the use of nonrenewable resources such as energy (Leveau et al. 2019). Giraldo & Rosset (2022, p. 821; emphasis in original) state that focusing on technologies without also adjusting other axes of change would result in "*fake* or *junk* agroecologies." Yet, these concerns may be more related to how the technology is implemented, managed, and used, as well as to how new technological opportunities are embedded in a larger picture of agroecological transformations rather than reflecting a fundamental contradiction. Bellon-Maurel & Huyghe (2017, p. 1) state that "…it is absurd, as it is sometimes read, to oppose agroecology and technology." Likewise, Leveau et al. (2019) report that information and communication technologies can be used in agroecological agriculture to support the application of its different principles without distorting them and that a responsible perspective should be taken, without taking the decision-making power away from the farmers (Bellon-Maurel et al. 2022).

4.2.3.2. Breeding technologies. New plant breeding technologies that include genetically modified and gene-edited crops[5] offer large potential for sustainable agriculture and food security (Qaim 2009, 2020). For example, new breeding technologies can contribute to improved crop yields, lower application of fertilizers and pesticides, and an increased resilience of crops to extreme climate events. Important breeding goals to increase pest and disease resistance will lower the need for pesticides and reduce yield variability (Bailey-Serres et al. 2019, Qaim & Zilberman 2003). A further focus is on developing crops with increased nutrient use efficiency so that fertilizer use (and its losses to the environment) can be reduced while maintaining or increasing crop yields (Bailey-Serres et al. 2019, Miao & Khanna 2020). New breeding technologies may also contribute to increasing diversity in agri-food systems. For example, it can be used to domesticate new and/or neglected crops and wild plants more rapidly than with traditional breeding technologies (Fernie & Yang 2019). Instead of focusing breeding activities on a small number of crops, new breeding technologies thus may allow efficient expansion of this scope, which would contribute to enhancing agrobiodiversity and dietary diversity (Qaim 2020). With the increasing diversity of crops and cropping systems, breeding for lower-input systems, and a range of different crop systems (intercropping and mixed, strip, or relay cropping, etc.), challenges for crop breeding will increase (Wuest et al. 2021).

Major obstacles in public and policy debates regarding new breeding technologies include the perceived risks to biodiversity, the environment, and human health associated with new plant varieties. This may derive from the breeding process itself and/or be related to the particular traits developed (Grossniklaus et al. 2020, Kearns et al. 2021, Qaim 2020). Synthesis studies do not indicate clear differences with other breeding technologies (Leopoldina 2019, NAS 2016). Further concerns are related to the feasibility of coexistence with organic and genetically modified–free agriculture and aspects of transparency within value chains and labeling (Eur. Comm. 2021, Qaim 2020). Another crucial aspect is the risk of the "disappearance of some conventional food production" (Lemarie & Marette 2022, p. 38). Moreover, the economic implications of (or different regulations of) new breeding technologies and distribution of economic rents across actors remain crucial aspects of public and policy debates (Purnhagen & Wesseler 2019, Wesseler et al. 2019). Also, questions of intellectual property rights are a key element of discussions (Jansen 2015). The European Commission (Eur. Comm. 2021, p. 57) points out that "stakeholders have different and often opposing views on these aspects."

The regulation of new breeding technologies differs substantially across countries and is highly dynamic (Buchholzer & Frommer 2022, Qaim 2020). Whereas Europe is more restrictive, countries in the Americas, for example, already use new breeding technologies. More specifically, the United States, Canada, and some South American countries have classified genome-edited crops (as long as they do not contain foreign DNA in the end product) as equivalent to conventional breeds (Buchholzer & Frommer 2022).

Despite their potential for agroecology, new breeding technologies are often seen as false solutions (see also Giraldo & Rosset 2022). Stassart et al. (2018, p. 3) even comment that the development of agroecology in Belgium is actually "rooted in public opposition to GMOs as the crystalization of the neo-productionist paradigm."

To address this, Niggli (2015a, p. 149), among others, calls for "a comprehensive culture of innovation" in organic agriculture and agroecology that also embraces technological innovations

[5] See, e.g., Buchholzer & Frommer (2022), Leopoldina (2019), NAS (2016), Grossniklaus et al. (2020) for definitions.

such as breeding technologies (see also Andersen et al. 2015). Moreover, Lotz et al. (2020, p. 21) conclude that "genetic engineering and agroecology certainly have synergy," especially owing to the opportunities of facilitating integrated pest management practices by making crops less vulnerable to pests and diseases. Similarly, Lemarie & Marette (2022) call for a coherency check of how the regulation of new breeding technologies can be integrated coherently to also contribute to goals in the Farm to Fork Strategy (see also Purnhagen et al. 2021). Recently, the European Commission concluded that new breeding technologies "have the potential to contribute to sustainable agri-food systems in line with the objectives of the European Green Deal and Farm to Fork Strategy" (Eur. Comm. 2021, p. 2).

Future debates should disentangle the question of new breeding technologies from specific agricultural practices, intellectual property rights, and distribution of economic rents. de Wit Montenegro (2022, p. 733) asks whether "agroecology and CRISPR can mix?" and discusses various reasons why agroecology and new breeding technologies do not integrate well. They suggest a push toward technology sovereignty (de Wit Montenegro 2022),[6] so that the use of new (breeding) technologies is clearly centered in farmers' preferences and local communities. In this way, "people's rights to make decisions about and cocreate technologies" (de Wit Montenegro 2022, p. 750) can be reflected and communities' collective knowledge and power can be used (which may not imply perfect harmonization of divergent epistemologies and ontologies). New breeding technologies may contribute to democratizing the breeding of improved crops, e.g., via participatory breeding (Colley et al. 2021).

5. SYNTHESIS OF PERSPECTIVES TO ENHANCE AGROECOLOGY AND CONCLUDING REMARKS

The challenge of developing sustainable agri-food systems is immense. However, agroecology is a promising approach to contribute to this ambition. It has gained much attention in recent decades with an increasing number of examples of its positive effects on agri-food systems. In this review, we have tried to understand to what extent agroecology can be scaled up to become the global model for sustainable agriculture and food production (**Figure 7*a***).

Revisiting the conceptual development and definition of agroecology, we point to its gradually expanding scope embracing the entire global food system. This includes economics, policy, the governance of transformation, and an increasing number of perspectives to capture system complexity, such as scales, SDGs, and sustainability dimensions, but also activities and codesign approaches. However, we also see convergence and agreement regarding the understanding of agroecology, but a concise definition effectively integrating its different perspectives, elements, and principles is pending. The term agroecology, which has not changed despite a widening of its scope, may also need attention.

Through a comprehensive literature analysis, we found that overarching publications addressing the full scope of agroecology, including its implementation, are largely missing. Instead, most peer-reviewed publications cluster into two main groups focusing on either the crop-soil system and related practices or the larger agri-food system. Further clustering shows that eight subgroups identified fall in either one or the other cluster, with little overlap among these, and show different dynamics regarding increasing or decreasing numbers of publications in recent decades. We also identified topical areas that received relatively little attention so far and that we have addressed here in more detail.

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[6]More specifically, de Wit Montenegro (2022) outlines six principals for technology sovereignty: It (*a*) focuses on technology for people, (*b*) values food providers as tech providers, (*c*) localizes tech systems, (*d*) puts control locally, (*e*) builds knowledge and skills, and (*f*) works with nature.

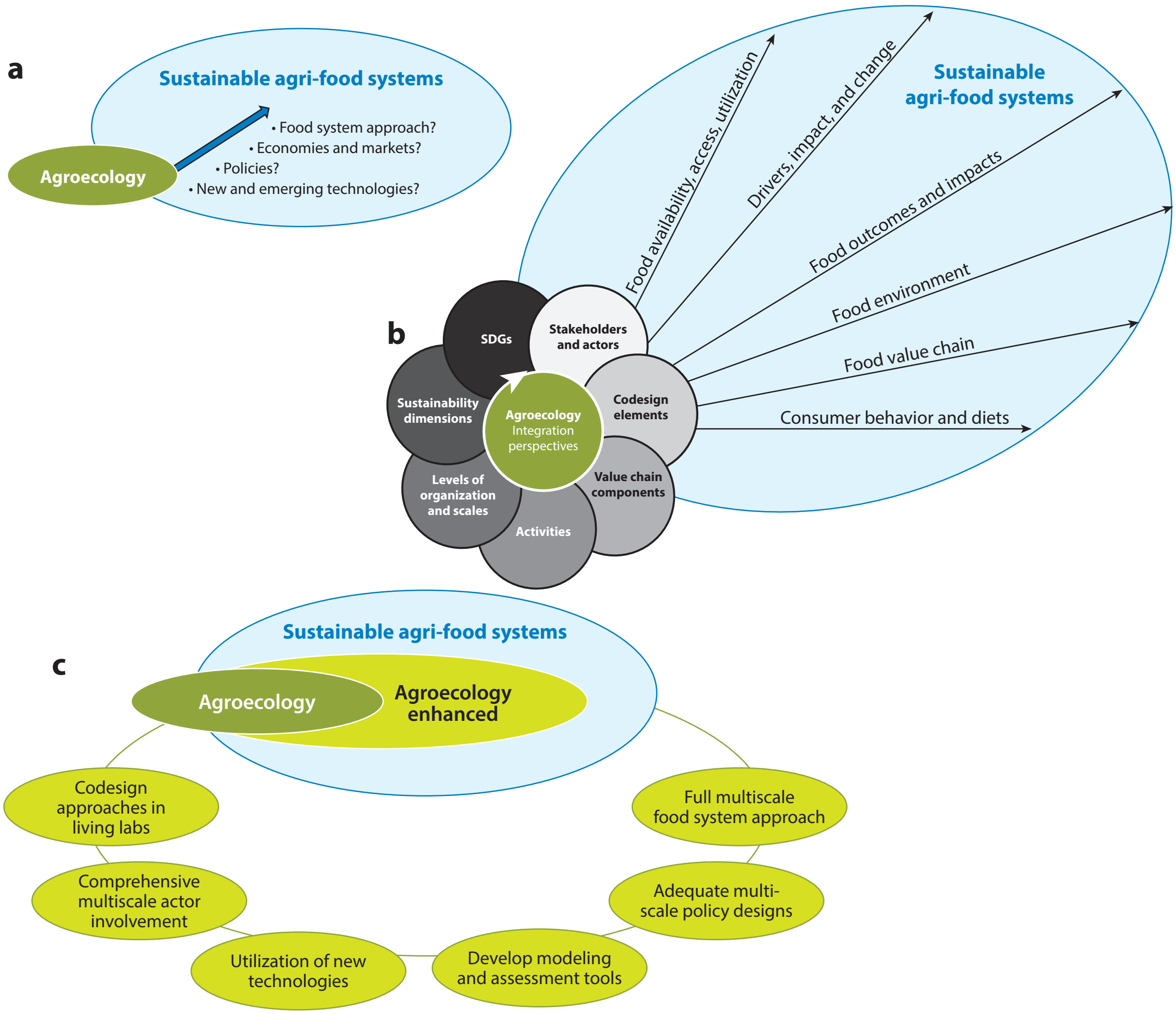

Figure 7

Agroecology for sustainable and resilient agriculture and food systems. (*a*) Scope of this review with important perspectives addressed, (*b*) the demand for integrating system perspectives of agroecology and food system characteristics (see also **Figure 5**), and (*c*) important areas of attention for enhancing agroecology to support the development of sustainable agri-food systems.

We noted that research on agroecology and food system science are not yet well integrated (**Figure 7*b***). A comprehensive food system approach including an analytical framework comprising local to global processes of ecosystem dynamics, value chains, markets, policies, and related codesign processes is also largely missing. Developing links to other research communities in food system research, economics, and policies could be beneficial in this regard. Jointly developing available monitoring, modeling, and assessment tools will be essential for agroecology to further develop its scientific basis, considering its widened scope.

Our analysis reveals that the consideration of new and emerging technologies such as digitalization and new breeding technologies can complement other steps to facilitate an agroecological transformation and contribute to more sustainable and resilient agriculture. However, important critical points and open questions remain.

We show that economic considerations of agroecology and the identification of its potential benefits for all agri-food system actors are key elements to broaden its use. Here, systematic assessments and further evidence are needed across different scales, farming systems, and agro-climatic zones. Moreover, we identify enabling and limiting factors that currently hinder broadening the use of agroecology along entire food value chains globally.

We identify the important role of policies. Although many countries have started considering agroecology in theory, national policy frameworks, large policy shifts, and multinational policy frameworks are still rare. Policy support is usually motivated by the assumption that agroecology can effectively and efficiently contribute to developing sustainable, resilient, and fair agri-food systems. However, such policy efforts should be embedded in broader policy perspectives and approaches. For example, these would comprise a focus on a holistic food system policy, addressing the role of different food system actors and a shift to healthy diets and a fair food system (De Schutter et al. 2020). Policies can create an enabling environment for innovation of solutions that are appropriate in the regional and local context (Pereira et al. 2018), ideally based on sustainability indicators. This also comprises the support of farmer-to-farmer networks and the improvement of farmers' access to knowledge (Lampkin et al. 2020). Policies can also create an enabling environment to integrate new technological opportunities in sustainable agri-food systems with agroecology such as digitalization and new breeding technologies. Finally, national policies need to account for implications for other countries, e.g., consequences of leakage and the telecoupling effects of policies. Overall, we identify six areas of needed attention in order to further enhance agroecology as a global model of sustainable agri-food systems (**Figure 7*c***).

1. Full multiscale food system approach: This would link local and regional solutions to global relationships determining the food system dynamics and interactions with related systems (**Figure 6**). This integration should consider relevant processes, relationships, actors, stakeholders, drivers, sustainability indicators, and the respective assessment methods across all scales.
2. Comprehensive multiactor involvement: This would consider all relevant actors and stakeholders at all relevant levels of organization and scales. This includes policy makers, food producers, upstream companies, retailers, and consumers as well as insurance companies and related industries and researchers avoiding inequalities and power asymmetries (Jacobi et al. 2021).
3. Codesign approaches in living labs: Living labs would facilitate such joint development, evaluation and testing of policies, innovations including new production systems and food networks, and new technologies considering all relevant actors and stakeholders at multiple levels of organization.
4. Monitoring, modeling, and assessment tools: These would monitor and assess the sustainability of agroecology-related system changes representing all dimensions of sustainability (environmental, social, and economic) at multiple scales. These will also require developing comprehensive data infrastructures and data management, modeling, and assessment capabilities.
5. Openness to and utilization of new and emerging technologies: Such utilization would untap the full potential of agroecology to support the transformation toward sustainable agri-food systems and engage all relevant actors and stakeholders.
6. Adequate policy design: This would support a full multiscale food system approach based on a holistic food system policy framework that integrates local/regional policies with national and global policies for more sustainable agri-food systems.

From a research perspective, we see an important need to support the development and implementation of an overarching analytical framework for agroecology, integrating food system components, levels of organization and scales, dimensions of sustainability, and more specifically, SDGs with the respective indicators to measure system impact and change. This can provide important evidence on possible contributions to bigger policy goals as well as benefits, costs, and risk. Such an overarching framework needs to be developed together with approaches for its implementation and operationalization. For this, it will be necessary to develop and use new or available monitoring networks, models, data infrastructures, impact assessments, and scenario analysis capabilities to support the development of and transformation toward sustainable agri-food systems. Successful development and implementation of this framework will require new research modes with diverse actors, including practitioners and policy makers, working together with researchers in a codesign process.

Although agroecology represents a promising approach to support the development of sustainable agri-food systems, other types of agriculture have a similar goal, such as organic farming, sustainable intensification, and regenerative agriculture. Given the complexity of these goals and the ever-limited scientific understanding of this complexity, different paths and a diversity of approaches from these different types of agriculture to reach the same goals may be possible, but they will require clarity and transparency about terms and approaches (IDS & IPES-Food 2022). Therefore, such diversification in agricultural approaches could offer colearning benefits in the interest of the overall goal of developing sustainable and resilient agri-food systems. This will require a culture of open engagement and exchange where scientific evidence should play an important role.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

F.E. acknowledges support from the Deutsche Forschungsgemeinschaft (DFG; German Research Foundation) under Germany's Excellence Strategy–EXC 2070–390732324. We thank the editor and two anonymous reviewers for valuable feedback on an earlier version of this review.

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