

Agroecology-The Case of Cereals

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Transformative agroecology has been recognized as a stepping stone to achieving several Sustainable Development Goals (SDGs), due to its great potential to build climate change-resilient farming systems while enhancing ecosystem services and reducing biodiversity loss. Understanding the agroecological elements that underlie the sustainability of an agroecosystem is an urgent matter, serving as the foundation for designing a truly transformative agroecosystem.

Keywords: agroecology ; biodiversity ; climate change ; rice ; sustainable agriculture

1. Introduction

Scientific advances have fueled the global growth in the agricultural sector for nearly a century, enabling producers from different countries to deliver abundant food domestically ^[1]. For example, the adoption of various agricultural technologies developed during the green revolution era in the 1960s has doubled the global production of the big three cereals—rice, wheat, and maize—within a mere two decades ^{[2][3]}. It was not until a half-century later that the sustainability of the revolution began to be questioned, especially with regard to the increased use of agricultural inputs that can affect soil health and the environment at large ^{[4][5]}. With an estimated 10 billion mouths to feed by the mid-century, a greener yet high-tech farming revolution is inevitable. In 2015, the United Nations created the blueprint to achieve a more resilient future, which includes a set of 17 interlinked Sustainable Development Goals (SDGs) that are universally applicable to all countries. Each of the goals outlines a specific set of targets that are interconnected in addressing different aspects of the global issues that call for holistic approaches ^[6]. Attaining global food and nutrition security will underpin the achievements for many SDGs, primarily SDG 2 that aims for zero hunger and SDG 3 that targets good health and well-being ^{[7][8]}.

Environmental ecology plays an important role in balancing the impacts of stresses on the ecosystem structure and function within the Earth's biosphere. Carbon dioxide, the most prevalent greenhouse gas (GHG) that drives climate change, continues to rise globally with urban areas accounting for three-quarters of its emissions ^{[9][10][11]}. A recent study conducted by Clark et al., 2020 ^[12] demonstrated that the global GHG emissions from food production alone may cause the temperature to rise approximately 1.5 °C by 2050 and 2 °C by 2100. It was also reported that there is a pressing need for viable climate-smart agricultural practices and a change in eating habits and food waste behavior to reach the Paris Agreement's goal of minimizing the rise in global temperature to well below 1.5 °C ^{[12][13]}. In addition to building resilient food systems, it is worth noting that dietary diversity will also help restore the approximately 75% crop genetic diversity that was lost during the past century, mainly due to the prevalent monoculture ^{[14][15]}. This is also in line with the targets for SDG 13 and SDG 15, aiming to combat climate change and halt biodiversity loss, respectively.

Sustainable agriculture, by and large, embraces the environmental, social, and economic conditions that challenge food and nutrition security ^{[11][16][17][18]}. To address the current sustainable development challenges facing the Earth, which is increasingly vulnerable to climate change, it is imperative for researchers to ensure that their research findings are relevant and comprehensible to society ^{[8][14]}. In this regard, recent years have witnessed a growing interest in adopting the emerging agroecological approaches to sustainable food systems in many countries, with crop diversification being one of the leading strategies ^{[18][19][20]}. Although the term agroecology was first coined in the 1920s, many different branches of agroecology have been developed since then, and these varied ideas about the field have caused confusion among researchers and the public at large ^{[11][21][22]}. Additionally, the current knowledge about agroecology in terms of recent developments and future trajectories to improve cereal production is scarce.

2. Deciphering Agroecology: The Ticket to a Sustainable Future

To build food systems that are ecologically, economically, and socially sustainable, a lifecycle of innovation needs to be established to pave the way for scientific information to deliver important benefits to the society—and this can be achieved through agroecology. Connecting science, farming practices, and social movements, agroecology has emerged as one of the leading strategies to achieve sustainable agriculture, whereby holistic approaches such as diversified farming are

adopted towards reorienting agricultural systems for farmers [6][20][23][24][25][26]. Mimicking nature, agroecosystems focus primarily on food production through the best use of ecosystem services such as pollination, maintenance of soil fertility, and hydrological services without damaging these resources.

Through the lens of science, agroecology is a discipline based on agronomy and ecology, whereby the design and management of resilient food systems hinge largely on the dynamic interactions among organisms and their environment. It is characterized by several environmental aspects, including nutrient cycling, energy flows, and dynamic population regulation [21][27][28]. The term agroecology is not new to the scientific world and has in fact been around for almost a century. First described in 1928, the key ingredient of agroecology at that time was the ecological methods used in research on commercial crop plants. It remained as a purely scientific discipline until the 1960s when environmental movements began primarily due to concerns over the impacts of the use of toxic chemicals (such as pesticides) on the environment. Consequently, agroecology emerged as an agricultural practice in the 1980s, aiming mainly at improving food production and quality while avoiding environmental impacts [21][26]. Since the 1990s, agroecology has gone beyond science and begun to look at social involvement, with major agroecological transitions at a significant scale. The economic and social factors have crept into the design and management of sustainable agroecosystems that rely on research-based practice [21][27]. Unlike conventional supply chains, agroecology focuses on circular food systems where producers and consumers are connected through an alternative distribution network [29].

Transformative, integrated approaches such as agroecology are essential to reduce the environmental footprint of agriculture, which maintains or improves the health of ecosystems that can safeguard food security in the twenty-first century [29][30]. Climate change is predicted to aggravate heat stress and cause diverse and location-specific impacts on agricultural production [31]. Climate change-induced alteration in the dynamics of pest, pathogen, and weed populations could make the situation worse [1][32]. The maintenance and enhancement of biodiversity in agroecosystems might be the solution for future pests and disease management [33][34][35][36]. The past two decades, particularly the last five years, have witnessed a growing interest in agroecology among different actors such as researchers, farmers, and decision-makers. In 2018, the Food and Agriculture Organization (FAO) identified ten interlinked and interdependent elements of agroecology (Figure 1), which can help countries to operationalize and manage agroecological approaches or transitions [37]. There is a growing global consensus on the importance of these elements in providing guidance to policymakers, practitioners, and stakeholders in transforming food and agriculture that contributes to multiple SDGs, mainly SDG 2, SDG3, SDG 13, and SDG 15 (Figure 1). Understanding the agroecological elements that underlie the sustainability of an agroecosystem is an urgent matter, serving as the foundation for designing a truly transformative agroecosystem.

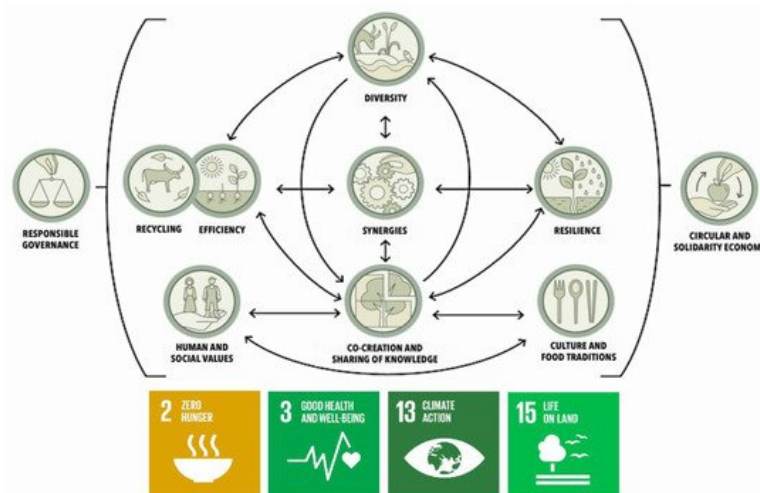


Figure 1. The ten interlinked and interdependent elements of agroecology that guide countries to transform their agricultural systems and to achieve multiple Sustainable Development Goals (SDGs), notably SDG2, SDG3, SDG13, and SDG15. (Adapted with permission from Food and Agriculture Organization of the United Nations (2018) FAO).

3. Ecosystem Services Enhancement in Cereal Crops through Agroecological Approaches

The post-green revolution agricultural systems generally succeeded in supplying adequate food to global markets. Nonetheless, the high-external input and resource-intensive agricultural systems have caused serious environmental issues, from increasing the levels of heat-trapping GHGs to soil depletion and biodiversity loss [2][14][36]. Biodiversity, a key feature of the Earth's biosphere where life exists, plays an essential role in ecosystem service [38][39]. Among multiple components of biodiversity, plant diversity has emerged as the principal determinant of various ecosystem goods and services, which include carbon sequestration, pollination, and soil nutrient retention [15][36][39][40][41][42]. Taking into account

the fact that increased climatic stress can adversely affect the development and functions of plants, particularly crops, there is a need to extend the proof of concept for greater diversity and ecosystem services ^{[43][44]}, and to understand the synergies between agroecological approaches and ecosystem services for a resilient future ^[45].

Several predictive models inferred that the production of most cereals, the most globally important group of crops, would reduce due to climate change ^{[31][44][46][47][48][49]}. On a positive note, recent years have witnessed a trend in sustained cereal production through agroecological innovations (Table 1). These innovations, which mimic or augment natural processes, are capable of improving farming systems in a variety of ways, from mitigating climate change due to reduced use of inputs or greater resource use efficiency, to increasing crop productivity and farm income. In cereal-based cropping systems, agroecological approaches have been adopted in several countries to harness biodiversity and ecosystem services (Table 1). One notable example is the “Toki to Kurasu Sato” (also known as Living in Harmony with Toki) rice certification system, whereby the koshihikari rice fields in Sado resembled the natural habitat of the critically endangered bird, the toki-crested ibis (*Nipponia nippon*) ^[50](Figure 2). Since its initiation in 2008, this certified low-input rice system has been a successful breeding ground for the bird, with more than 200 birds currently giving back to the fields by preying on small animals that cause loss to rice production. Figure 2 shows the relevant agroecology elements within the “Toki to Kurasu Sato” rice certification system along with a suite of SDGs that could be achieved through the system. It is worth noting that different biological agents, such as ducks and fish, have been utilized as weed control in some rice fields ^[51].

Crop Species	Agroecological Element	Relevance	Country	Reference
Rice-Cassava	Diversity Synergies	Intercropping to augmenting income and better use of the crop growth resources	South-west Nigeria	^[52]
Sorghum-palisade grass/guinea grass	Synergies Efficiency	Evaluating grain yield, forage biomass production and revenue through intercropping	Brazil	^[53]
Maize-Bambara groundnut	Diversity Efficiency	Evaluating planting density against yield production within intercropping to determine the best combination	Nigeria	^[54]
Wheat-Soybean	Diversity	Intercropping to increase yield produce per unit area	United States	^[55]
Sorghum-Cowpea	Diversity Synergies Efficiency	Evaluating crop yield to fertilization	East Africa	^[56]
Wheat-Maize-Soybean	Efficiency	Determining the characteristics of nitrogen uptake, use and transfer	China	^{[57][58][59][60]}
Rice	Co-creating and sharing knowledge Synergies	Adopting System of Rice Intensification (SRI) to enhance rice growth using less inputs	Indonesia, Thailand, Vietnam, Cambodia and Malaysia	^{[61][62][63]}
Cactus-Sorghum	Efficiency	Intercropping to evaluate irrigation efficiency	Brazil	^[64]
Rice-Water spinach	Diversity Efficiency Synergies	Intercropping to improve yield and uptake of Si and N nutrition content whilst managing disease and pest control	China	^[65]
Amaranth/ Maize-Legumes	Diversity Efficiency Synergies Recycling	Intercropping to evaluate the methane (biogas) and biomass yield production	Germany	^[66]
Maize-Barley/Vetch	Synergies Efficiency Recycle	Evaluating cover crop management to reduce water pollution due to nitrate leaching under actual and climate change conditions	Spain	^[67]
Maize-Soybean	Efficiency Synergies	Evaluating nutrient uptake within intercropping patterns	China Canada	^{[68][69]}
Spring Barley	Efficiency Recycling	Nutrient recycling through use of cover crops and cereal straw management	Denmark	^[70]

Maize-flowering partners	Diversity Efficiency Synergies	Intercropping with flowering partners to enhance biodiversity and to evaluate the effect on plant growth, silage yield, and composition yield	Germany	[15]
Rice-grass	Efficiency Recycling Synergies	Intercropping upland rice with forage grasses to increase food production, enhance land use per unit area, nitrogen (N) cycling and profitability.	Brazil	[71]
Rice/fungi/water spinach/alligator flag (Cd removal)	Diversity Synergies Efficiency	Evaluating the phytoremediation effect on plant growth and Cd accumulation properties through intercropping.	China	[72][73][74]

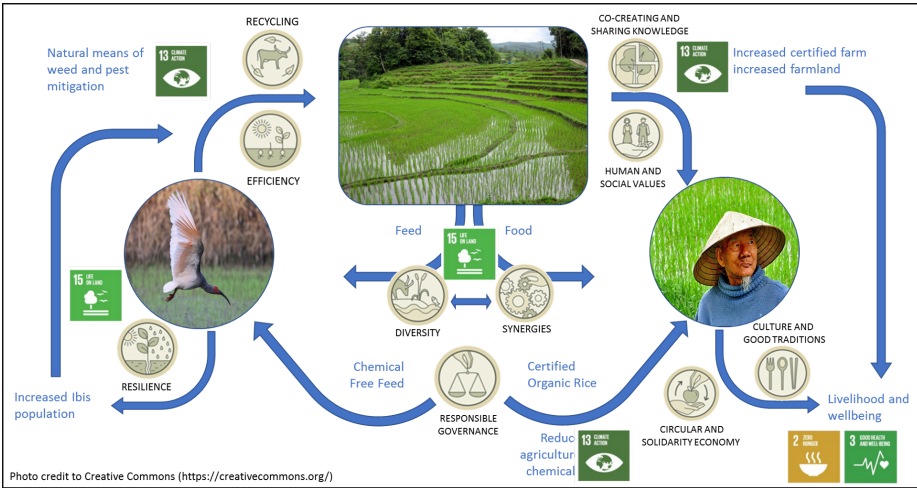


Figure 2. Relationship of the

"Toki to Kurasu Sato" rice certification system with agroecology elements and Sustainable Development Goals (SDGs). This certification system is peculiar to Sado, aiming mainly at balancing agricultural promotion with environmental generation and promoting safe and sustainable rice production.

In recent years, the diversification of staple cereals (such as wheat, maize, and rice) and the systems in which they grow, have been increasingly promoted as one of the key strategies to make future agriculture sustainable [2][14]. Several gluten-free, underutilized (or orphan) cereals and pseudo-cereals have made it closer to mainstream research, particularly quinoa and millets [1][14]. Crop diversification has been proven to enhance crop yields, biodiversity, and several ecosystem services such as water and soil quality [35][36][69][75][76][77][78][79]. It is also worth noting that the diversification of cereal-based cropping systems has been the dominant approach for agroecological transitions in many countries (Table 1), possessing enormous potential to ensure food and nutrition security while conserving and enhancing the use of natural resources [80][81][82]. A recent study conducted by Zonneveld et al. (2020) [81] identified seven fundamental steps for how researchers and practitioners can work with farmers, particularly smallholders in tropical and subtropical regions, to deliberate on and decide the best options to diversify farm systems in the midst of climate change.

Rice is the second most important cereal crop after wheat, with Asia being the largest producer and consumer. Countries such as Malaysia, Cambodia, Vietnam, and Indonesia have adopted the System of Rice Intensification (SRI) farming method that provides the farmers a means to address the challenges of producing rice for the steadily growing population that is coupled with limited resources and constraints of climate change [61][62][63]. The SRI is an agroecology production system that adopts changes in management practices for rice cultivation that enhances the growing environment for the crop towards sustainable agriculture. Compared with traditional rice production practices, this method of rice farming adopts the agroecology aspect where rice is produced by focusing on optimizing available resources, i.e., soil, water, seeds, nutrients, solar radiation, and air to augment yield per unit area [82][83]. The encouraging output from the SRI methods has also been extended to other crops (i.e., wheat, maize, finger millet) [82][84] to achieve sustainable food production.

The strategies for crop diversification, based on several studies conducted on 120 crops globally, can be assigned to five broad categories: associated plants, intercropping, crop rotation, cultivar mixture, and agroforestry [76,85]. Intercropping is considered one of the leading categories and has been adopted in cereal-based agroecological farming systems in many countries (Table 1). A recent global-scale analysis on the adoption of intercropping between cereals and grain legumes demonstrated that this practice can improve the use of soil resources (such as nitrogen and phosphorus) while reducing the requirement for synthetic fertilizer [75]. Although grain legumes have the natural ability to fix nitrogen symbiotically, they are often less efficient than cereals in terms of using soil nitrogen [8][69][75][77][79][86]. Hence, cereal-grain

legume intercropping can help increase the overall nitrogen use efficiency in a cropping system. This practice also has other potential advantages, including increased yield per unit area and reduced pest problems, as shown in Figure 3. In addition, intercropping also enhances and preserves biodiversity for pollinators because they contribute up to 35% to the global crop yield [15]. Several studies have shown that incorporating flowering plants into the intercropping system increases the diversity of the pollinators, thus indirectly increasing production [15][41]. Crop rotation is another popular practice for managing agroecosystems, being the fundamental component of organic systems. Legumes are often the crop choice in crop rotation because they are capable of enhancing nutrient cycling and availability to other crops [28][42][69][87].

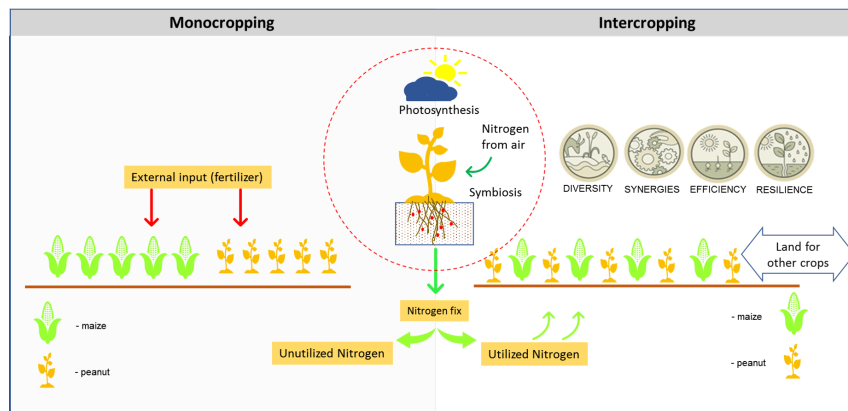


Figure 3. An example of how an

intercropping system between cereal (maize) and legumes (peanut) can enhance soil health and diversity, relative to a monocropping system.

4. The Way Forward

4.1 Seizing Momentum for a Sustainable Twenty-First Century Agriculture System: A Perspective

Agroecology has existed for nearly a century; however, it was not until recently that it became the focus of sustainability research and the policy discourse on food systems. Agroecology has continuously evolved since its inception, from nothing more than an ecological slant for sustainable agriculture to a “science for and with society” approach that fits the food sovereignty paradigm of the 21st century [21][26][88]. By focusing on circular—rather than linear—food systems, agroecology innovates the structure of the whole food system, including activities that give rise to major climate forcings, such as intensive use of inputs, transport, and processing [26][29]. It is imperative to note that agroecology means different things to different actors, such as researchers, policymakers, and farmers, and can be adopted at various scales, from urban plots to large-scale farms. Social networks in agricultural settings should be improved by building on or strengthening interaction among different actors to foster social cohesion and socioeconomic synergies, creating a food system that is based on localness, participation, and fairness [24]. In a world in which ecological processes are evolving rapidly, researchers must ensure that their research findings are relevant and comprehensible to the society. Greater provision of knowledge and skills development is perhaps the key to ensuring the future of resilient agriculture and agroecology.

Although the agroecological approach is increasingly recognized as a mainstream strategy to establish sustainable food systems amid climate change, adopting it requires a far greater effort than to continue the conventional farming systems that are dominated by monocultures. A range of measures, actions, and policies guided by scientific evidence are essential to realize a truly transformative agroecology that is tailored to the local context [88][89]. According to Gliessman (1998) [22], the universal principle is that an agroecosystem is more likely to be sustainable when it has a higher structural and functional similarity to the natural ecosystem in its biogeographic region, which provides the basic services that benefit humanity. Major ecosystem services—which include provisioning, regulating, supporting, and cultural—have been widely studied in the past two decades [11][90]. With the rise of new global strategies (such as the UN Decade on Ecosystem Restoration 2021–2030), it is clear that a more specific knowledge is needed to enhance the resilience of ecosystem services—such as a definitive set of principles for building resilience—to sustain the future of a warmer, hungrier world.

Although a one-size-fit-all approach to ecosystem service enhancement does not yet exist, a set of interdependent generic principles have been established to guide the operations plan in different contexts [91], where the definition and purpose of each principle have been thoroughly reviewed. Among the seven established principles, maintaining diversity and redundancy is at the forefront, supporting and co-occurring with other principles that involve social contexts [91][92]. Generally, the elements of social-ecological systems that exhibit diversity (such as genes, species, livelihood strategies, and governance institutions) work together with functional redundancy, where functionally similar elements can be substituted for each other to enhance the resilience of ecosystem services [93]. Figure 4 presents the major differences between agroecological farming and intensive farming that requires high external inputs, illustrating why agroecology is a

better farming approach. Given that most ecosystem services are governed by multiple species or other system elements, agroecological approaches should be carefully designed based on how these elements respond to different disturbances in a particular biogeographical region, for example, drought in South Africa, in addition to the timing of their contributions to ecosystem services. It should be noted that excessive levels of diversity or redundancy may increase complexity and inefficiency, which may in turn lead to reduced capability for adaptation to slower, ongoing change ^[91]. Balance is the key to identifying and implementing agroecological innovations for a sustainable future.

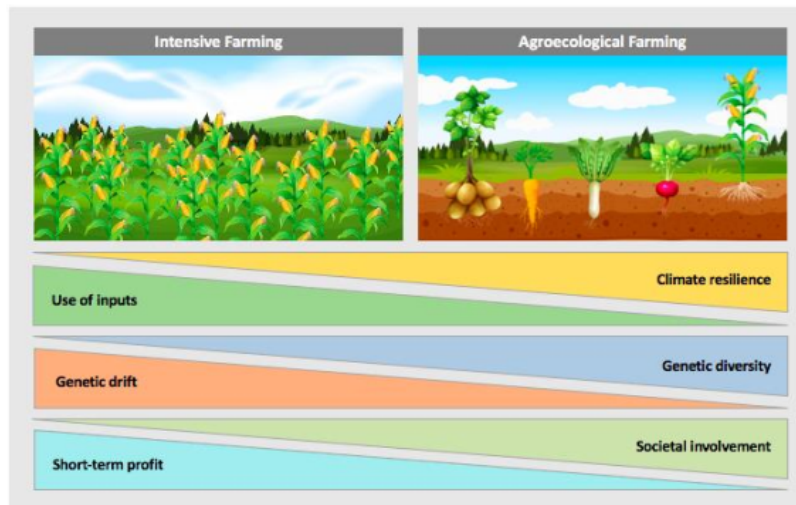


Figure 4. Major difference between

intensive farming and agroecological farming

Ongoing climate change, rapid population growth, and unprecedented crises, such as the recent coronavirus pandemic, are among the major global challenges for humanity in the twenty-first century, exacerbating many weaknesses in the current food systems that may trigger societal collapse in developing or underdeveloped regions ^{[1][94][95][96]}. To eradicate global hunger and malnutrition without affecting the natural systems, it is crucial to foster understanding of complex adaptive systems and social-ecological dynamics through experimentation by researchers, learning, and participation of policymakers and farmers. Countries should start or continue promoting more ecologically friendly agricultural systems while reducing ecosystem stressors (such as pollution) from other economic activities and creating a more equitable distribution of food. It is worth mentioning that consumers play an indirect role in maintaining ecosystem services, mainly by their willingness to change preferences towards more diverse diets.

Although it is a challenge to expand and engage the participation of diverse actors, the collective effort is inevitable in responding to changes and disturbances to ecosystem services. Regardless, the success of a transformational agenda depends ultimately on an enabling policy and legislative and institutional environments. These include capacity enhancement of key actors, incentives to help businesses invest or expand, fostering relationships among different actors such as farmers and consumers, helping shape improved diets, and reducing food loss and waste ^[97]. It is also important to take bold policy actions, especially in tackling the undesirable trade-offs in ecosystem services, such as between provisioning services, or among the SDGs ^{[98][99]}. Both short- and long-term impacts of agricultural policies on productivity and sustainability should be clearly identified and understood; reaching this goal relies mainly on the effectiveness of the engagement between policymakers and researchers and farmers ^[100]. In short, a “science for and with society” approach is needed to achieve both food security and sovereignty—and agroecology is the answer. Nonetheless, the adoption of agroecology could prove challenging for most, if not all, actors involved.

4.2 Future Challenges in Agroecology

To date, various agroecological approaches have been adopted for sustainable farming systems in many parts of the world (Table 1). Although the adoption of agroecology is fraught with possibilities, there is still a large amount of work to be done by different actors, primarily the research communities that are responsible for designing climate-resilient systems and transferring the relevant knowledge to other actors. First, they need to determine the most feasible agroecological approach for a particular system based on localness and valid experimental data. Then, they need to communicate how effective the selected approach is to other actors, including policymakers and farmers. It is also important for researchers to address the misconception about the possible scale of agroecology, namely, that it can only be adopted in small-scale farms and requires a large amount of labor ^{[101][102]}.

In view of the fact that an agroecological transition is a complex, multi-level process involving environmental, economic, and social aspects, the development of an effective knowledge transfer strategy in agroecology is inevitable to achieve a successful transition. The challenge is to create a universal strategy that yields a dynamic actor network, bridging the knowledge and/or communication gap between different actors, particularly researchers and farmers. According to Aare et

al. (2020) ^{[25][103]}, farmers often find it difficult to understand the advice given by agricultural advisors in managing a climate-resilient farming system, thus hindering farmers from giving new approaches, such as agroecology, serious consideration. Another challenge for farmers is the lack of training and development programs relevant to this emerging field, hampering the processes of knowledge sharing ^[102]. As such, researchers and policymakers must address these challenges while identifying what drives farmers' choices. The development of local or regional policies for sustainable agriculture through agroecology can accelerate the progress towards achieving more resilient food systems.

To build confidence in agroecology, legislation relevant to the field should be enforced, although the implementation can be associated with challenges and requires a long-term commitment. For example, a legislation framework for biodiversity conservation should be carefully developed and implemented to stop biodiversity loss. The overall success of the 20 Aichi Targets set by the Convention of Biological Diversity (CBD), which aimed to stop biodiversity loss, has been low after a decade of efforts and is not uniform across targets ^{[104][105]}. Hence, the Aichi Targets will be replaced by the Global Biodiversity Framework (GBF) for the period of 2021–2030, which is facing the challenge of implementation at national scales. Structuring a framework that focuses on ecosystems and processes while synergizing more extensively with existing global agreements on biodiversity conservation could be the means to overcome this challenge ^[105]. Ultimately, the aim of the newly enacted legislation should focus on understanding and adopting agroecology. Thus, enhancing the ecological and socio-economic resilience of food systems can be enhanced in both local and global contexts.

5. Conclusions

The recent coronavirus crisis is a powerful reminder that food and health are the overriding essential needs of humankind. Revamping ecosystem services during a century that is undergoing rapid climate and social-ecological changes is an enormous challenge. Although agriculture plays a pivotal role in food production and safeguarding ecosystem services, it also reaps the benefits from services that are functioning effectively. Agroecology has been hailed as the win–win solution for agriculture in the twenty-first century, promoting sustainable food production while also mitigating climate change. Because cereals are the most globally prevalent group of crops, more research must be devoted to agroecological innovations in cereal systems. Researchers must then communicate the relevant information to other actors, such as policymakers, farmers, and consumers, to support a greener, healthier, and more sustainable global agricultural system. Our review identifies the opportunities for and barriers to the adoption of agroecology, and highlights that this “science for and with society” approach is one of the most feasible ways to build a resilient future.

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