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Review

Climate Change, Food Security, and Health: Harnessing Agroecology to Build Climate-Resilient Communities

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Abstract: Climate change threatens human health, food security, and ecological sustainability. In marginalized and vulnerable communities around the globe, there is a crucial need to initiate actions to reduce adverse climatic impacts and support sustainable development goals (SDGs), particularly on food and health. Climate change's multidimensional and complex impact on food and health has prompted calls for an integrated, science-based approach that could simultaneously improve the environment and nourish development-constrained communities. This paper examines a transdisciplinary practice of agroecology that bridges the gap between science, practice, and policy for climate action. We also analyze the significance of agroecology in building climate-resilient communities through sustainable food systems. We assert that the marriage of science and local knowledge that addresses access inequities through agroecology can lessen the impact of climate change on rural communities to achieve healthier, more sustainable, and equitable food systems. Furthermore, a transformative agroecological paradigm can provide farmers with a host of adaptive possibilities leading to healthier communities, improved food security, and restored lands and forests that can sequester greenhouse gases. Based on our findings, we call on the science and policy communities to integrate agroecology as part of the broader strategic approach to climate change adaptation and mitigation.

Keywords: climate change resilience; agroecology; food security; sustainable food systems

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1. Introduction

The United Nations Security Council recognizes that "climate change is the defining issue of our time" [1]. It poses a clear and present danger to global peace and security, as well as the health and well-being of communities. The Intergovernmental Panel on Climate Change [IPCC] [2] WGII Summary Statement says: "The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all. (Very high confidence)." Climate change has exacerbated the frequency and severity of extreme weather events such as heat waves, droughts, floodings, and storm surges [3,4]. For instance, heat waves affect people's cognitive performance [5] bring about a higher risk of death from ischemic strokes, especially among women [6]. The year 2022 is set to be one of the warmest years on record, with the 2013–2021 period ranked among the top ten warmest years in the history of climate record-keeping [7]. Apart from the threat to human lives, the rise in temperatures causes high evapotranspiration and wildfires and may create conditions that facilitate the breeding of new pests, pathogens, and diseases that negatively impact crop growth in their various lifecycle and deteriorate human health [8,9]. While the world grapples with current climatic stressors, recent projections [10] reveal that the intensity and frequency of these extreme weather events will increase and become even more destructive in regions such as sub-Saharan Africa (SSA) where adaptive capacity is relatively lower [11].

The impacts of climate change on health and food systems are multidimensional, which complicates the identification, attribution, and assessment of these impacts [12]. Despite this complexity, it is apparent that the enduring impacts of climate change are particularly felt by rural areas in underdeveloped countries with low adaptive capacities. From the perspective of the Sustainable Development Goals (SDGs), the impacts of climate stressors on food systems are particularly concerning as SDG 2 (Zero Hunger) is crucial for meeting other goals, including SGDs 3 (health), 1 (poverty), and 13 (climate action). As a result, scientists have highlighted the need for an integrated approach to addressing food and health crises and for consolidated, strategic, evidence-based actions to reduce risks and impacts to meet global societal needs [2,13].

The need to build resilient health and food systems to meet societal needs is urgent, yet the present threats of climate change vastly outpace current measures to achieve these resilient systems and tend to exacerbate current climate change and food insecurity challenges. For instance, evidence indicates that the current capitalist agricultural system's emphasis on mechanized production, biological overrides, and mass production has failed to feed the world's poor and protect the environment [11,14,15]. These failures are also evident in the growing food insecurity in many parts of the world [2]. In particular, smallholder farmers, who produce more than half of the total global food supply, are the most food insecure [11]. It is important that actions are taken to make the global farming systems more resilient, especially in smallholder contexts.

Furthermore, there is a pressing need to move away from the current unsustainable farming regime that separates winners from losers, hinges on high-input application, and causes ecological catastrophes, all while making food security a mirage for many smallholder farmers with few financial resources [16]. The United Nations Sendai Framework for Disaster Reduction 2015–2030 provides a seven-point plan that links with development, climate change, and resilience building to achieve these global goals. Similarly, the recent International Union of Food Sciences and Technology (IUFoST) Global Food Summit discussed the urgent need to develop strategies for sustainable and resilient food systems, primarily through integrated science-based approaches. The point of convergence among these global scientific communities is aptly captured in the UN Secretary-General's statement that "we are in a world in which global challenges are more and more integrated, and the responses are more and more fragmented, and if this is not reversed, it's a recipe for disaster" [17]. The scientific community's consensus is that there is a need for more place-specific and integrated interventions that bring together the scientist, government, civil society, and local farmers to address climate change. Secondly, climate change interventions must follow a holistic approach to resilience by generating diverse pathways for incremental and transformational change towards more sustainable farming and food systems while also ensuring environmental sustainability.

Building on key findings from a knowledge synthesis report on climate change impacts on food and health, with emphasis on the need to engage local knowledge in climate resilience building [18], this paper examines the critical role that agroecology (a sustainable food production approach) can play in building communities that are resilient to climate change by strengthening food systems and health against climate stressors. We analyze the evidence on the threat climate change poses to food and health in vulnerable populations, identifying knowledge gaps and presenting evidence of the transformational role of agroecology for building community resilience. Ultimately, the study contributes to the literature on ongoing efforts to transition food systems to approaches that enhance human and environmental health and become more sustainable and equitable to health, thus fulfilling the SDGs.

2. Materials and Methods

This paper is informed by key findings from the "Building Climate Resilient Communities: Living Within the Earth's Carrying Capacity" knowledge synthesis report [18]. The report indicated that "to address the climate crisis, a more ambitious, strategic, and collaborative approach to adaptation is required" (p. 3). This approach should especially help "small, rural, remote, northern, and Indigenous communities adapt to climate change impacts" (p. 3). We leverage findings from this report to further understand how pro-poor and context-specific, community-based adaptation approaches can aid in building climate resilience. This report has been prepared in the context of studies [2,13] emphasizing the need to integrate science to address food and health-related climate issues within the earth's carrying capacity and to move away from fragmented responses in an increasingly integrated world.

This paper explores agroecology, defined as "the science and practice of applying ecological concepts, principles and knowledge (i.e., the interactions of, and explanations for, the diversity, abundance and activities of organisms) to the study, design and management of sustainable agroecosystems" [19], as a nature-based approach to building climate-resilient communities. A multi-track retrieval approach (Web of Science, Scopus, Google Scholar) was used and then a strategic evidence review undertaken to collect evidence that complements the report to understand the role of agroecology in building resilience to climate-related health and food systems.

Studies have suggested that the use of a rapid review is acceptable when scholars are experts in the field and have undertaken closely related searches [20–22]. Building upon the search criteria used in an earlier study, we undertook a rapid review of social science literature on agroecology and its relation to climate resiliency. This is considered a rapid review and not a systematic search as not all criteria for systematic review were met, including the use of two reviewers. Instead, our approach combines expert knowledge, existing literature from a prior systematic evidence review, and searches in databases for additional papers.

In terms of the inclusion criteria, we considered studies from 2012–2022 that specifically discuss agroecology's role in food security, health, and climate change resilience in developing countries. The search included all languages, but we focused on studies written in English. We relied both on peer-reviewed and grey literature (practitioner literature, government reports and policy briefs), including qualitative and quantitative studies across multiple disciplines, to explore this topic. Screening was made on the basis of abstract, title, and full text review. Exclusion criteria included studies before 2012, non-peer reviewed publications, and studies on sustainable agriculture that did not specifically refer to any of the agroecological practices described in subsequent sections.

An assessment of the literature from Building Climate Resilient Communities: Living Within the Earth's Carrying Capacity produced 35 papers. Next, on the Scopus and Web of Science databases and Google Scholar, we searched for articles using the following search terms: agroecolog OR agro-ecolog OR "crop diversi" OR agroforestry AND "climate change" OR "climate resilience" OR "food security" OR "food systems" OR "community health" OR "climate adaptation" OR "healthy communit. On Scopus and Web of Science, we retrieved a total of 677 articles. After a series of article screenings, including duplicate removal, abstract screening, and full text review, we identified 44 articles (as shown in Table 1). These studies provided crucial insights on the relative role of agroecology in climate resiliency in resource-constrained contexts. These articles were discussed by the researchers over a series of meetings and themes were developed in the process.

Table 1. Summary of database search and number of abstracts/papers reviewed.

Search Terms	Search Method	Number of Abstracts Screened	Number of Papers Reviewed
agroecolog OR agro-ecolog OR "crop diversi" OR agroforestry AND "climate change adaptation" OR "climate resilience" OR "food security" OR "food systems" OR "climate adaptation" OR "healthy communit"	Previous reviews and expert knowledge	35	12
	Scopus	351	18
	Web of Science	291	14
	Total	677	44

While our approaches produced crucial insights, we acknowledge some limitations. First, it is possible that not all studies were identified given that this not a systematic review. Secondly, due to our exclusion criteria, we may have missed some relevant studies, such as those not reported in English. Despite these limitations, this study is among the first to assess the role of agroecology in building climate-resilient communities in the Global South. The next section of this paper provides a detailed overview of the state of climate-induced food and health impacts facing undeveloped regions and the need to focus on these areas.

3. Climate Change in Resource Constrained Contexts: A Need for Resilience

Climate change is a threat multiplier that affects the major dimensions of food security, including production, access, utilization, and stability. Climate change is worsening the already fragile state of food security across smallholder farming communities. In predominantly rain-fed farming systems, climate variability manifests itself in floods and droughts, which pose significant risks to crop failure. Droughts and floods are associated with increased soil erosion and decreased soil micro-organism activity, respectively [23]. According to the United Nations Environment Programme [24] and IPCC [2], if the current effects of climate change are left unchecked, the total loss of agricultural output in sub-Saharan Africa could reach 11% in 2080. While poor people are the most impacted by food insecurity, crop failure due to climate variability has broader implications on poverty and food accessibility because food scarcity influences food prices [25].

Climate change is impacting the health and well-being of farming communities and their health systems. The impacts are expected to intensify in the face of minimal adaptation capacities in poor-resource contexts. In SSA, for instance, the underdeveloped nature of health systems heightens public health risks. Researchers interrogating occupational health and safety have identified farming as a particularly stressful endeavour. Farming is associated with several health risks due to the physical demands, exposure to hazardous materials, and the conditions under which farmers work [26].

Recently, climate change, which is particularly devastating to smallholder farmers, has been recognized as a critical threat to public health and well-being [27]. Climate change affects human health directly through hazards such as storms, floods, heat waves, and more nuanced pathways such as diseases, disruption of agricultural systems, and population displacements [28]. The literature has mainly emphasized the biophysical health challenges associated with climate change and food insecurity; however, studies indicate that extreme climate change hazards and other environmental changes have significant direct and indirect impacts on people's psychosocial and mental health [27–30]. A study found that seed germination failure is a constant worry among farmers in semi-arid Ghana due to dry spells and rising temperatures, predisposing them to future mental health problems [29]. Despite this growing evidence, climate change and rural health connections have been largely underexplored.

The mental health impacts of climate change can vary from minimal or moderate stress (i.e., ranging from mild anxiety to sleep disruptions) to more acute clinical disorders such as depression, post-traumatic stress disorder (PTSD), and suicidal ideation [28,30]. According to Gruebner et al. [31], peritraumatic experiences are highly associated with acute stress during or after extreme climate events, which may subsequently lead to PTSD. For example, Bei et al. [32] found that mental distress (specifically PTSD) was a significant after-effect of flooding. The magnitude of floods was directly correlated with the severity of their impact on mental health [32]. The loss of lives, properties, and displacement of people due to floods may also lead to grief and other psychosocial stress [33]. For example, Bandla et al. [33] found that 20%, 28.3%, and 36% of flood victims in India were diagnosed with depression, anxiety, and PTSD, respectively. Similarly, smallholder farmers in semi-arid regions are vulnerable to drought-induced mental challenges; prolonged droughts and severe erratic rainfall patterns have been associated with inadequate social functioning and psychological fatigue [28].

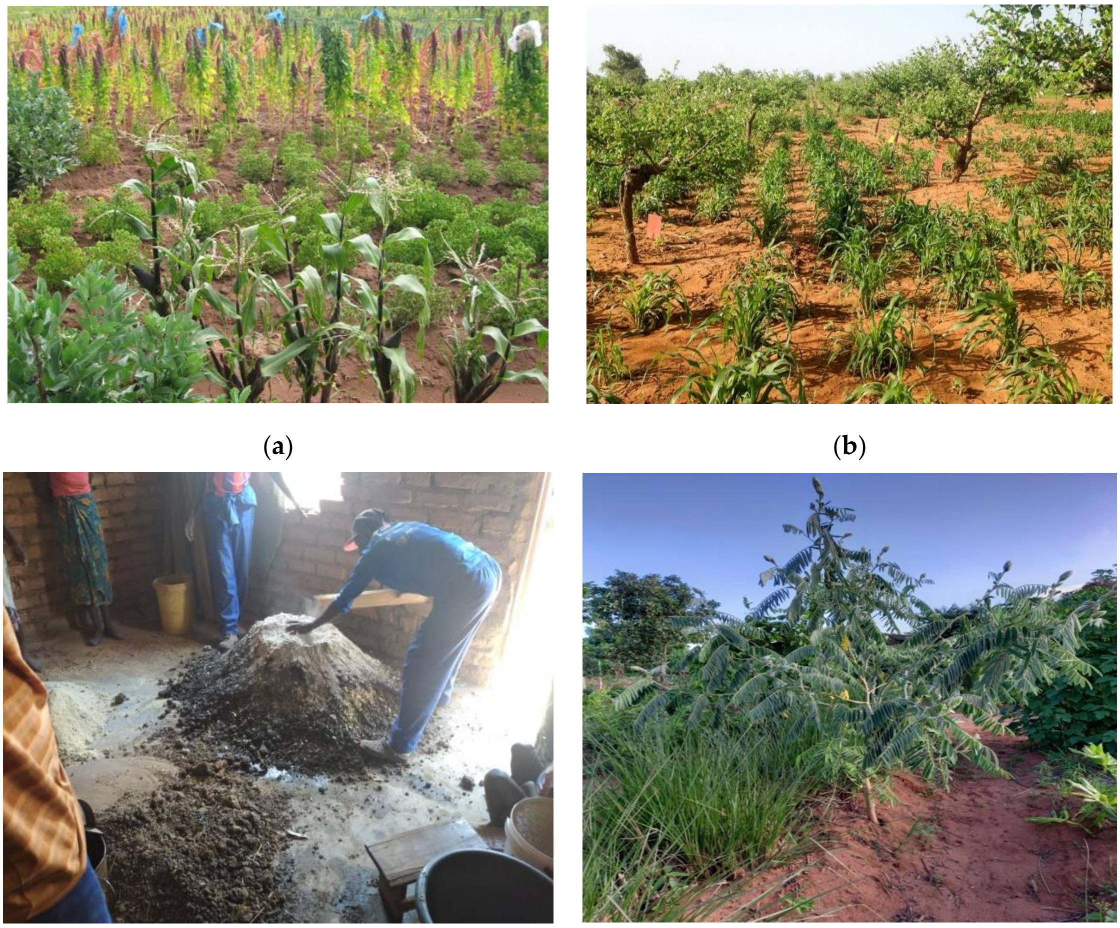
It has also been established that awareness of the global loss of biodiversity can be related to feelings of hopelessness and depression [28]. Awareness of the climate crisis can also lead to distress, anxiety, and feelings of impending doom [34]. On the other hand, there have been reports of positive psychological well-being or "post-traumatic growth," which leads to feelings of altruism, purpose, and optimism [28,34]. Extreme weather events can also lead to significant morbidity and mortality. Direct catastrophic impacts on communities can occur during severe weather events, and indirect effects are observed. For instance, reduced crop yields and the inability of smallholder farming households to purchase food are further related to the widespread malnutrition situation in, for example, SSA. According to Lloyd et al. [35], increases in atmospheric carbon will reduce the iron, zinc, and protein content in grains, directly affecting nutrition.

Climate change continues to affect the lives and livelihoods of millions living in developing countries and there is pressing need for resilience. Resilience is evolutionary process of change which involves capacity building toward minimizing crises and maximizing opportunities concurrently [36]. According to the IPCC, resilience is the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation [2]. Adaptation in this context refers to behavioural changes, primarily through incremental changes and learning from past adversities to minimize crises and vulnerability [37], while transformation entails radical changes that may even put the system's survivability at risk [38]. The capability to adapt or transform is, however, not an intrinsic quality. Adaptive and transformative capabilities derive from the 'availability,' 'accessibility,' and 'acquisition potential' of capitals—the resources by which local communities utilize to achieve their livelihood objectives—in a balanced proportion within any environment characteristic of exposure and vulnerability. Broadly, these capitals have been categorized into five groups, viz. human, social, natural, physical, and financial capitals [39].

Amidst the socio-ecological challenges of climate change and the urgent need for climate resilience, some scholars have advocated for the integration of agroecological production in the past-2020 global biodiversity framework [40] and for the future of sustainable and just transitions [41], because it can simultaneously address food insecurity and improve agrobiodiversity. The next section examines agroecology, including its principles and components and how this transdisciplinary, integrated approach could improve climate resilience.

4. Agroecology as an Integrated and Interdisciplinary Approach

Agroecology is widely understood as "an integrative study of the ecology of the entire food system, encompassing ecological, economic and social dimensions" [42] (p. 100). In practice, agroecology is a systems-based approach that mimics the normal functioning of the local environment without external inputs to create a natural balance of soils through a process of nutrient recycling [43,44]. Unlike conventional farming practices that involve synthetic inputs (e.g., chemical fertilizers), agroecology embraces the connectivity of systems (social, ecological, political) as part of the broader food production process by aligning crop production with the unique realities of communities, including their resources and constraints. As an integrated science approach, agroecology does not espouse a simple approach to agricultural production. Instead, it promotes sustainable methods by considering interdependencies between humans and nature and other social factors such as poverty and inequality [45], which can be understood through transdisciplinary research methods. To this end, agroecology subscribes to a knowledge-intensive approach by building on indigenous (local) knowledge systems, which smallholder farmers have developed and relied upon for centuries, in adapting to harsh environments without depending on artificial fertilizers and pesticides [46,47]. Some of these agroecological practices are shown in Figure 1.



(**a**) (**b**) (**c**) (**d**)

Figure 1. (**a**) Diverse crops growing in a field as part of an on-farm conservation Project in Ecuador. Photo credit: Biodiversity International, available at https://www.bioversityinternational.org/research-portfolio/conservation-of-crop-diversity/ (accessed on 9 October 2022); (**b**) An agroforestry photo showing a farmer planting millet in the middle of existing trees in Niger. Photo credit: Cgiar.org, available at https://www.cgiar.org/news-events/news/towards-sustainable-seed-systems-in-eastern-and-southern-africa/ (accessed on 12 October 2022); (**c**) Smallholder preparing Bokashi organic fertilizers. Photo credit: Soils Food and Healthy Communities; (**d**) A *trephosia* planted by smallholder farmers in Northern Malawi which is used for producing insecticides for controlling insects on farms. Photo credit: Soils Food and Healthy Communities.

Agroecology comprises different ecosystem enhancement approaches including crop diversification, agroforestry, mixed farming, and other sustainable land management practices [48]. Collectively, agroecological practices hinge on specific organizing principles that have been established and thoroughly reviewed. These principles are summarized by Migliorini and Wezel [49], the High-Level Panel of Experts [41], and more recently, by Wezel et al. [50]. The principles are further categorized under biophysical and social-relational (economic, political, and cultural) tenets. The biophysical principles are: (1) recycling of biomass to maintain soil fertility—mimic the normal functioning of the local environment without external perturbations in order to create a natural balance of soils through a process of nutrient recycling [43,44]; (2) enhancement of functional biodiversity through the minimization of energy, water, soil, and genetic resource loss—by ensuring species diversity and plant genetic materials at the farm, field, and landscape level, which is integral to sustainable food production. This is achieved through utilizing natural processes that create beneficial interactions and synergies among various aspects of the agroecosystem in ways that harness agrarian productivity; and (3) diversification of species and genetic resources in the agroecosystem, and enhancement of beneficial biological interactions and synergies [50]. This principle is highlighted through sustainable ploughing techniques, cover crops integration, agroforestry, and terracing to reduce runoff [51].

The socio-relational principles underpinning agroecology include: (1) the creation of collective knowledge, and coping ability—this principle addresses the power imbalance inherent in food systems whereby women are poor farmers who are primarily sidelined in managing and utilizing productive resources. Agroecology tries to bridge this gap in two ways; the first one is the feminist approach. This method creates awareness about women's power, promotes their participation in social decision-making, educates women on different types of technologies and helps them become agents of change. The second one is the policy approach that promotes women's empowerment policies [52]; (2) enhancement of farmers' independence; fairness, participation in land and natural resource governance; and (3) the privileging of the value of diversity in knowledge and know-how [41,49]. Thus, agroecology hinges on collaborative participation of researchers and knowledge systems, allowing decolonization of research and the identification of norms for governing ecosystems and improving agriculture systems [53]. These principles are reflected in certain agricultural practices, marketing strategies, and food system governance in agroecological farming systems.

Agroecology has three strands. First, as a scientific discipline, agroecology is rooted in multiple disciplines, including agronomy and ecology, soil science, and plant physiology [43,54]. This implies that agroecologists can harness and apply the knowledge from these various disciplines in an integrated way and turn them into science-based actions to reduce the risks and impacts of climate change on agricultural production, as will be discussed in later sections. By integrating critical insights from multiple disciplines, agroecology reconciles agricultural development with biodiversity conservation by providing options for sustainable intensification based on principles derived from ecology, biology, and cultures [43].

Secondly, as a set of agricultural practices, agroecology involves utilizing natural processes that create beneficial interactions and synergies among various aspects of the agroecosystem in ways that harness agricultural productivity. The approach employs place-specific methods for cultivating food in a way that considers the uniqueness of the place and the sustainable land management practices for sustainable and healthy food production. These sustainable land management practices include agroforestry, mixed farming, composting, and legume integration [50]. In this context, agroecology as agricultural practice privileges the context-specificity of food production by considering the place's local climate, soils, topography, and culture to tailor an approach that considers the socio-ecological context within which the local food system operates. Agroecology thus relies on a clear understanding and consideration of the specific food system context (region, period, system complexity, involved actors, institutional structures, etc.).

The third strand is agroecology as a social movement. Agroecology is not only a tool for sustainable food production but is closely associated with agrarian social movements, including food sovereignty movements. Agroecology seeks to empower farmers by protecting their ability to participate fully in the food system, from the breeding, production, selection, marketing and distribution stages, as well as how the food is used and who benefits from this use [55,56]. As a social movement, it focuses on the entire food system, which indispensably includes the consideration of political ecology and aspects of equity, participation and empowerment, food sovereignty, rural development, and local marketing systems [51]. This aspect of agroecology aligns with the IPES Food's [57] call for more substantial participation among policy and decision-makers, including farmers, at local, regional, and global scales, and other supply chain actors as crucial to transforming the current unsustainable agricultural regime. Thus, the social movement context of agroecology emphasizes the protection of fundamental human rights, promotes equal participation and indigenous knowledge, and harnesses the wisdom of traditional farming systems where the experiences of smallholder farmers, the majority of whom are women, are leveraged for more inclusive and sustainable food production [43,58].

Based on the principles mentioned above and associated strands, it can be deduced that agroecology does not espouse a simple approach to agricultural production. Instead, it lends its interdisciplinary and pluralistic perspective to promote sustainable methods by taking into account interdependencies between humans and nature, as well as other social factors such as poverty and inequality [45]. At a pivotal time like this, characterized by mass production and consumption and unsustainable utilization of environmental resources, agroecology is best placed to provide the unique interventions needed to bring about a sustainable change in regions most vulnerable to climate-induced food and health insecurities. The next section discusses the transformational power of agroecology in climate change adaptation for effective resilience building.

5. How Does Agroecology Build Climate-Resilient Communities?

5.1. Stimulates Sustainable Food Production

With its wide-ranging soil and land management options, agroecology presents significant opportunities for climate change adaptation and mitigation in resourced constrained regions. A recent systematic review of agroecology on a global scale revealed that about 78% of studies found that agroecological interventions such as crop diversification, soil management, livestock integration, and pest management were positively associated with food security and nutrition. Crop diversification, for example, ensures that farmers can get food from their farms over a longer duration due to the difference in maturity rates of the crops grown. Thus, these farms are resilient to climate variability, which builds household resilience to climate-related weather events. An ethnographic study of traditional agroforestry in Mexico found that households consumed over 60 different foods, the majority of which were sourced from family farms. The cultivation of varying cereal crops, legumes, and perennial tree crops provided the dietary diversity needed by the households and ensured that food was available year-round [59]. It has also been noticed in some contexts that agroecology practising households were healthier than their counterparts who practised conventional agroecology. A study in Tanzania, for instance, revealed an increased dietary diversity among children living in agroecological practising households [60]. Given that children are among the most vulnerable to food insecurity and health, consuming diverse diets could mean that they can gain the necessary nutrients needed for a healthy and active life. In addition to food security, some studies have found that food security achieved through agroecological interventions was associated with positive mental health outcomes [61]. The net effect of these benefits is that households and communities become more resilient to climate change and its impacts.

In addition, agroecological participatory approaches, defined as the " active participation of farmers in designing, implementing and assessing agroecological farming strategies to improve yield through knowledge co-production and sharing" [55] (p. 31) are closely associated with the adoption of sustainable land management practices. For instance, farmers who engaged in a farmer-to-farmer-led agroecological intervention through the integration of local knowledge in Northern Malawi were more likely to engage in sustainable land management practices, including legume intercropping, terracing, mulching, manuring, composting, and crop residue integration [62]. This is especially necessary for transitioning food systems to be more sustainable as studies have shown in many contexts that farmers do not necessarily gain adequate information from extension officers, especially in rural contexts, due to structural constraints and may be less likely to abandon their methods for environmentally friendlier practices. These structural reasons may range from language barriers, infrequent visitation, and a low level of expert knowledge [63]. Yet, Son et al. [64] assert that integrating local knowledge into farming enhances community resilience to climate change.

5.2. Agroecosystem and Forest Restoration for Carbon Sequestration

Evidence points to the fact that agroecology leads to the restoration of farmlands and degraded forests [65,66]. In a study examining the perceptions of deforestation, forest restoration, and the role agroecology, it was found that farmers who practise agroecology reported varied levels of forest restoration after applying agroecological practices on their farms compared to farmers who did not practise agroecology [66]. Agroecological practising farmers engaged in extended fallows and polyculture, which stimulated the revitalization of ecological functions that facilitate forest restoration and agroecosystems, ultimately increasing opportunities for carbon sequestration—more so than current capitalist monocultures. Agroforestry, legume integration, and crop diversification and composting, for instance, also have an indirect effect of reducing deforestation as the need for new farmlands will be minimized, while effective pruning could provide the fuelwood needs of households.

By integrating trees and other plants into farming practices, this system can promote healthy soil quality and better yields without excess fuel being used for tilling the earth. In addition, agroforestry fosters the protection of trees, which are suitable for carbon capture, increase habitat for various species, and contributes to coolness during hot months. According to Ramachandran et al. [67], agroforestry practices such as parklands (trees and crops) and alley cropping (trees planted in rows between crop fields) can provide 20–100% more carbon sequestration than monoculture systems. This farming system can also help protect watersheds and other bodies of water as trees filter pollutants and help retain moisture [67].

Agroecological farms have greater carbon storage capacities than conventional farms and are more energy-efficient [68]. For instance, energy efficiency levels were found to range from 10:1 to 30: 1 [69] on Cuban farms applying agroecological innovations compared to their US counterparts who used 50% more energy for 1 unit of food energy produced (i.e., 1:1.5). An analysis by Rakotovao [70] showed that tree planting, whether in an agroforestry or forestry system, had the most significant effect on differentiating carbon footprints among distinct clusters of smallholder farmers in Madagascar.

Contrasting agroecology with monocropping, it has been noted that conventional input-agricultural practices have resulted in the depletion of soil organic carbon levels over time due to over-reliance on synthetic fertilizers or manure management systems that do not restore lost organic matter back into the soil [71]. To counteract this loss of soil carbon, agroecosystems use organic manures and fertilizers to restore the fertility of soils. In addition, mixed farming systems that utilize different plant species on the same piece of land have been shown to improve soil carbon storage by using a wide variety of plants which complement each other. This is particularly advantageous in tropical areas where mixing species on a variety of farms contribute toward regenerating degraded agricultural lands and biomass.

5.3. Agroecology Widens Farmers' Scope of Adaptive Possibilities

Unlike conventional smallholder agriculture, which is mainly synonymous with monoculture, agroecological practices such as crop diversification, mulching, and agroforestry offer farmers a wide range of farm management options that are designed to protect agrobiodiversity, food security, and resilience to climate change [72]. For instance, agroecological practices reduce farmers' dependency on 'modern' agricultural inputs like inorganic fertilizers, weedicides, and other agrochemicals that have long-term negative ramifications on soil, water, and air qualities. The reliance on locally sourced materials for farming implies that households improve yield at lower costs, thus improving family savings—money that can be used for other purposes such as obtaining health care which makes households resilient to climate-related sicknesses. This is in addition to the fact that multiple crops mean that farmers can sell excess crops for income [73], and they also become seed secure for the next planting season [74]. Similarly, when farmers diversify their crops, they minimize their risk of total crop failure and commodity price volatility [75] so that when a particular crop fails, they can rely on other crops to meet their dietary needs. Moreover, when leguminous crops (e.g., beans and peas), which are rich in nitrogen, are planted together with other crops (e.g., millet or maize), they help fertilize the fields.

Within the context of smallholder farming, Nyantakyi-Frimpong et al.'s [76] assessment of an agroecological intervention in Northern and central Malawi indicated that farmers who practised agroecology were more likely to report household food security and dietary diversity than farmers who did not practise agroecology. This is because farmers rely less on input-intensive practices like inorganic fertilizer purchase and the cultivation of one crop variety, which makes these farmers more prone to crop failure in the advent of unfavourable rainfall patterns (see also Snapp et al. [77]). Global-scale analysis of intercropping of grain legumes and cereals revealed that the practice improves soil nitrogen (N) and, as such, reduces farmers' need for synthetic fertilizers by about 26% globally [68]. This is especially valuable in poor regions where farmers cannot afford to purchase chemical fertilizers to enhance the soil fertility on their farms. Chemical fertilizer prices and carbon footprints may also be reduced because of a reduction in global demand. Studies such as Sethuraman et al. [78], Mugendi [79], and Kumar and Nath [80] have also demonstrated crop diversity's role in landscape biodiversity, stimulation of species production, and the enhancement of ecosystem service provision through the rejuvenation of species rendered redundant in monocultural landscapes, as seen in Figure 2.

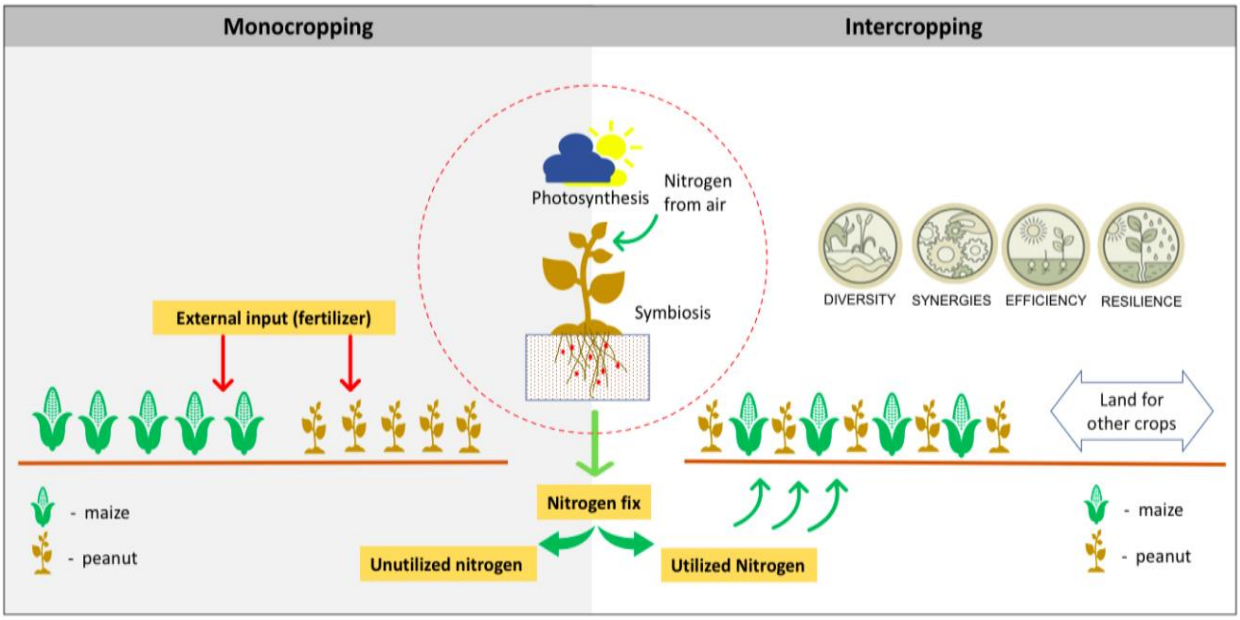


Figure 2. A depiction of how an intercropping system between cereal (maize) and legumes (peanut) can enhance soil health and diversity relative to a monocropping system. Adopted from [78].

Agroecology as a social movement can bring about empowerment and close gender gaps, which have long been characterized by the current agricultural regime [20]. Farmers are empowered by allowing room for active participation in designing and implementing farming strategies. Aipira et al. [81] note that bridging such gender gaps contributes to household and community resilience to climate change. By encouraging local participation and the use of locally available resources and knowledge, such as manure and compost and a deep understanding of the nature of agroecosystems in local areas and the principles by which such agroecosystems function, agroecology transfers ownership of the production process to local farmers which enables them to make decisions relevant to their situation and that suit local climatic conditions [82]. Due to its emphasis on traditional local systems, there is evidence to suggest that agroecology enhances the production of social connections. For example, Kansanga et al.'s [83] study of agroecology use in Malawi found a bidirectional relationship between agroecological practices and social capital among poor farmers.

Kansanga et al. asserted that agroecological principles like the co-production of knowledge typified by the agroecological intervention examined in the study led farmers to build more robust social networks and become more likely to receive support and help in facilitating access to productive resources like agricultural information, soft loans, or communal labour. That is because a just farm management system like agroecology offers opportunities to destroy power imbalances and empowers farmers in communities, increasing their access to resources and resilience [84]. Pfefferbaum et al. [85] present that both personal and community resilience is increased by the social capital that emerges from improved social connections and social networks.

6. Conclusions

Despite the diversity of case studies assessed in this study, the existing body of literature strongly supports agroecology as a sustainable food and land management system that can provide the twin benefits of improved food security and environmental sustainability for improved health and well-being. The most common agroecological practices include crop diversification, agroforestry, and mixed cropping and livestock systems. These practices involve replicating the normal functioning of the local environment without the introduction of external inputs. As such, agroecological innovations are relatively affordable, ecologically friendly, and align with the culture and traditions of people. These qualities make agroecology particularly beneficial to smallholder farmers in poor and middle-income countries, as they may be able to achieve food sovereignty in the face of the climate crisis.

The study strongly highlights that deploying sustainable agricultural practices such as crop rotation, crop diversification, legume integration, permaculture, and intercropping can create a pathway to building community resilience, including climate resilience. Specifically, agroecology improves agricultural productivity and food security, making diverse crops available that can improve dietary diversity and income for smallholder farmers. In addition, agroecology contributes towards the restoration of degraded lands and forestry [66], which improves carbon sequestration. As an alternative to industrial agriculture, agroecological practices such as agroforestry maintain habitats and connectivity for biodiversity and support ecosystem functions under climate stress. Increasing farm biodiversity will benefit farmers in a number of ways, such as pollination, pest control, nutrient cycling, soil fertility, and water regulation [77]. Furthermore, as a home-grown solution, this practice also increases farmers' adaptation possibilities by increasing their options by way of risk distribution, and diversification of income sources. Thus, the integration of agroforestry, crop diversity, residue management, mixed farming, and organic soil management bends the curve of ecological destruction, ensures sustainable food production, and improves ecosystem service provision [40,83].

Our study reinforces the call for greater investment in agroecological research [41]. The scientific community will benefit from continued research on agroecology that is informed by local food systems and is farmer led. However, for agroecological innovations to be effective in building resilient communities in resource-constrained regions, it is imperative that the right adaptation actions are taken in the right places and that local communities are involved in making decisions about their local environment. Farmer-to-farmer approaches, as suggested by research in SSA, is particularly important in helping to achieve a sense of belonging and for bridging the power gaps between the scientific community and farmers. While the research has demonstrated the transformative potential of agroecology, these benefits may not be achieved unless policy is developed at national, regional, and local levels. We therefore recommend the inclusion of agroecology as part of broader strategies for strengthening food systems in the context of rapidly changing climate.

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