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Perspective

Agroecology, technology, and stakeholder awareness: Implementing the UN Food Systems Summit call for action

Siyan Zeng,[1,2,3,*] Juan Li,[2,4] and Thomas Cherico Wanger[2,3,5,6,*]

SUMMARY

The global food system must meet the increasing demand for food, fiber, and energy while reducing environmental impacts. The UN Food System Summit (UNFSS) has made a clear call to action for a global food systems transformation. We argue that three major discrepancies remain, potentially delaying the urgent implementation of the call to action. First, Nature-based Solutions (NbS) are not sufficiently focused on agriculture, leading to funding allocation issues. Second, a mismatch of agroecology with technology innovations may slow scaling agroecological farming. Lastly, agricultural diversification must move beyond organic landscapes and into conventional agriculture. As a solution, principles of NbS should be clear on agricultural integration. Moreover, stakeholder awareness must increase that agroecology does not necessarily conflict with agricultural technologies. Future agricultural models must apply measures such as agricultural diversification in conjunction with technology innovations to then ascertain an overall timely and successful implementation of the UNFSS call to action.

INTRODUCTION

The global food system has been facing the twin challenge of meeting food, fiber, and energy demands of a growing human population and reducing the increasing environmental issues.[1] Agricultural land expansion has dramatically accelerated over the past two decades, and croplands used for global food production now cover 1,244 Mha with 49% of which occupying natural ecosystems.[2] Driven by the growing global food demand and inefficiencies of the entire food supply chain, from synthetic fertilizer production to waste management, the overall food system creates ~32% of global terrestrial acidification and 78% of eutrophication.[3] Furthermore, emissions from the whole food system have increased from 16 to 18 Gt CO_2e yr^{-1} from 1990 to 2015, respectively, attributing to 34% of total GHG emissions.[4] All these environmental externalities require a collective paradigm shift how agriculture is done in the 21st century.

The 2021 United National Food Systems Summit (hereafter UNFSS) united all stakeholders to facilitate a transformation toward a resilient and inclusive production system.[5] The UNFSS highlighted the important work on core topics for the global food systems transformation such as human diet changes[6] and new technologies such as cultured meat, genome editing, and vertical farming[7] for environmental benefits at a steady increase of agricultural outputs by about 1% per year.[8] A focus has been on agroecology, an integrated and dynamic concept to optimize management of food and agricultural systems with a focus on the interactions among plants, animals, and humans prioritizing a fair food system (HLPE 2019[9]). Agroecology is critical in the global food systems transformation, to achieve the Sustainable Development Goals (see https://www.un.org/sustainabledevelopment/),[10] and, thereby, to address the twin challenge of climate change impacts and biodiversity loss. As much research on agroecological principles and underlying agricultural diversification has already been done to support the way forward,[11,12] the UNFSS ended with a "call to action" to build on existing work and start with the global food systems transformation immediately.

While we fully support the call to action, we argue that three major discrepancies in agroecology, technology, and implementation limitation remain that—if addressed in a timely manner, can expedite the global food systems transformation. After reviewing the lessons learned from historical global food systems changes, we focus first on the discrepancy that Nature-based Solutions (hereafter: NbS) are underutilized in mainstream agriculture in the process of a transformation toward agroecology-based agriculture. NbS

[1]College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China

[2]Sustainable Agricultural Systems & Engineering Lab, School of Engineering, Westlake University, 18 Shilongshan Road, Hangzhou, China

[3]Key Laboratory of Coastal Environment and Resources of Zhejiang Province, School of Engineering, Westlake University, Hangzhou, China

[4]Department of Health and Environmental Sciences, Xi'an Jiaotong-Liverpool University, Suzhou, China

[5]GlobalAgroforestry Network.org, Hangzhou, China

[6]ChinaRiceNetwork.org, Hangzhou, China

*Correspondence: zengsiyan@westlake.edu.cn (S.Z.), tomcwanger@westlake.edu.cn (T.C.W.)

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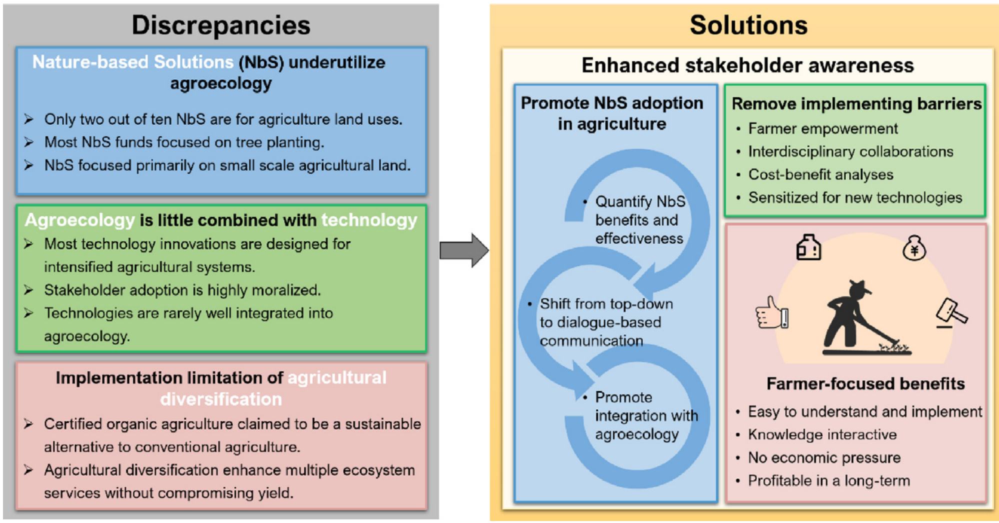

Figure 1. Overview of the discrepancies and solutions we propose to implement the UN Food Systems Summits' call to action immediately

Box colors match between discrepancies and solutions.

are actions to protect, sustainably manage, and restore natural or modified ecosystems to simultaneously providing human well-being and biodiversity benefits.[13] We see the discrepancy here that most NbS funds are targeting for instance tree planting campaigns for carbon sequestration but not specifically targeting agricultural landscapes,[14] which may result in funding allocation issues and a policy focus mismatch.

We then look into the discrepancy between agroecological implementation with advanced technologies. Agroecological practices are often said to not be effectively integrated with new technology solutions,[15,16] leading to missed opportunities for the food systems transformation. In short, agroecology is a dynamic concept that applies ecological principles to agricultural systems, ensuring a regenerative use of natural resources and ecosystem services while also addressing the need for socially equitable food systems, sensu HLPE.[9,17] Here, we limited the consideration of technology to supporting the complex process of the agroecological food system transformation and follow the classification of near-ready and future technologies that could accelerate this transformation (for in depth reviews see[7]).

Lastly, we investigate the discrepancy that agricultural diversification is not sufficiently implemented in conventional production landscapes, which underutilizes the vast potential of diversification. Agricultural diversification is the deliberate addition of functional biodiversity to agricultural systems at multiple spatial and/or temporal scales to achieve regenerating biotic interactions that provide yield-supporting ecosystem services.[18] Solutions to these three discrepancies must focus on increased stakeholder awareness of the effectiveness of NbS, agroecology with technology integration, and new technologies such as insect protein and cultured meat, and apply measures such as agricultural diversification to conventional agricultural systems for sustainable agricultural systems (Figure 1). Here, we reflect on these key findings and help to bridge policy implementation gaps effectively through enhanced stakeholder awareness across the food supply chain for transforming sustainable agricultural systems globally.

A BRIEF HISTORY OF FOOD SYSTEMS TRANSFORMATIONS AND THE LESSONS LEARNED

Depending on crop characteristics and producers, food production systems have seen different stages from a traditional to an industrialized food production transformation. First, farming has become more specialized, high-yielding, and in parts more regenerative than before. However, vast differences remain between crops and regions, for instance, between heavily industrialized wheat production in high income nations like the United States[19] and smallholder farmer cocoa production in lower income countries like Ghana.[20] The second trend is a shift from labor-intensive to land-intensive, and then to capital-technology-intensive food production. The number of farmers that can support their livelihoods with agricultural production is substantially reduced, as large-scale production has concentrated a large amount of land on a few family farms. China's agricultural sector is a prime example, where aging farmers are not replaced by younger generations but effective farming technologies.[18] Meanwhile, the transformation of family farms based on plant-livestock recycling systems into industrial monocultures has brought negative environmental impacts and agricultural pollution with a low resource recycling rate.[21]

Along with economic development and changes in food system-related factors, consumers are shifting from traditional food consumption to processed foods[22] and ultra-processed foods (UPFs).[23] UPF is a category of foods that have undergone a complex series of industrial processes, with the addition of a variety of food additives and are generally high in sugar, salt, and fat, but create convenient, ready-to-eat, and tasty food of which excess consumption can increase risks of many chronic diseases. For example, evidence from United Kingdom and the United States suggest that food environments, such as fast-food restaurants, supermarkets, and convenience stores are increasingly dominated by UPFs.[24] UPFs play a key role in the "nutritional transition" in the food systems transformation, when shifting from traditional diets to diets associated with obesity and non-communicable diseases. In contrast, shifting to healthy diets, with a more than 50% reduction in unhealthy foods such as red meat and UPFs, has been suggested to avert approximately 11.0 million deaths per year.[6] Diversified sources of protein would complement the global transition to healthy diets by providing competitive meat and dairy alternatives.[5] Thus, consumer awareness for healthy diets and novel food substitutes needs to vastly increase to build a green consumption model that guarantees human and planetary health.

However, the food system transformation toward industrialized food production and a higher degree of food processing all come with profound impacts on the environment. For instance, the whole food system as an increased demand for agricultural land and livestock production is causing 34% of global greenhouse gas emissions.[4] Agriculture-driven extinction risk is exacerbated for 1 million species, resulting in a substantial decline in ecosystem services such as pollination and biological pest control.[6] These environmental externalities of agriculture have received much attention[2,5] (Text S1–S4) and solutions based on alternative farming approaches, such as ecological restoration, ecological intensification, organic farming, and diversified farming have been proposed.[11,18,25] Besides, NbS for transformative agriculture are "the utilization of natural processes or elements in a properly deployed way, over a range of temporal and spatial scales, to provide a triple benefit: improving the resilience of agriculture and the livelihoods of farmers, mitigating and adapting to climate change, and enhancing nature and biodiversity."[26] Many hybrid NbS have been widely used for conservation and rehabilitation in agricultural production landscapes.[27] Moreover, agroecology is comprised of a set of principles, broadly defined as the integrative study to design sustainable food systems based on the ecological, economic, and social dimensions.[17] A research agenda for agroecology in large-scale farming highlights societal goals beyond economic productivity to support an agroecological transition.[28,29] In Italy, for example, modern agroecological practices such as highly diversified farming, olive agroforestry, and terracing are used in combination with socio-cultural and local diversity knowledge to stabilize or even enhance crop yields under climate change.[30,31] As NbS and agroecology are firmly on the policy table toward a sustainable food systems transformation,[28] here, we mainly focus on NbS in the agriculture sector to explore the potential of integrated effort of NbS and agroecology to jointly address issues of food security, climate change, and biodiversity loss.

In addition, certified organic farming is often considered a silver bullet to solve the global biodiversity crisis and provide healthy foods toward a sustainable food systems transformation.[7] However, reviews comparing organic to conventional farming found considerable yield gaps of as much as 180% in developing countries and certified organic agriculture requiring more land converted to agriculture to obtain similar yields.[12] In contrast, the adoption of diversification practices within conventional farming is likely to enhance multiple ecosystem services without compromising yields.[11] Agricultural diversification encompasses a wide range of farming practices that include but is not limited to crop, non-crop, soil, and landscape management.[18] When comparing diversification practice effects on ecosystem services, there is a wide range of outcomes for individual ecosystem services and between different diversification strategies such as agroforestry, intercropping, cover crops, crop rotation, or variety mixtures.[32] While several studies integrate results across cropping systems and a broad range of diversification practices within one cropping system,[11,33] we focus our later discussion primarily on food crop systems; however, the same principles can be extended to pastoralism, forestry, and among others. Some argue that external inputs and technologies can increase output efficiency in extensively redesigned diversified farming systems,[34] which may likely not reflect a nuanced view on the integration of technology in diversified farming systems. While there is strong evidence that a major transformation toward sustainable food production is needed, enhancing general awareness of solutions among NbS, agroecological practices, and agricultural diversification and the interlink with emerging technologies is still needed.[10,11,24] In the next section, we argue that discrepancies exist between the above solutions that may at least slow down implementation of a sustainable food systems transformation.

THREE DISCREPANCIES

Nature-based Solutions underutilize an agroecology perspective – Implications for funding availability and social benefits

Currently, NbS do not sufficiently focus on agriculture, but NbS in agricultural landscapes can support the global food systems transformation and provide co-benefits such as climate impact mitigation as well as water and biodiversity conservation.[26] NbS principles are effective nature conservation norms, provide inclusive and context-specific landscape-scale solutions, and focus on trade-offs between ecosystem and economic benefits, and hence, offer opportunities for policy and regulatory advancement.[13] When NbS is effectively integrated with agriculture, besides the outcome of (i) local and indigenous peoples, biodiversity-friendly development, and (ii) climate adaptation and disaster risk reduction, the most discussed is (iii) conserving biodiversity, reducing degradation.[35] For instance, by applying legal instruments to create a biosphere reserve can provide the benefit on protecting biodiversity and climate regulation and then promote the sustainable coffee production in Ethiopia.[27] Conversely, mismatched policies and regulations on agricultural environmental management needs can hinder the effective uptake of NbS,[26] such as the lessons learned from European applications of the rural development payment schemes.[36] However, the International Union for the Conservation of Nature's seminal work suggests that only two out of ten NbS project are for agriculture land uses[37] and NbS implementation to date has focused primarily on tree planting for carbon sequestration,[14] marginal lands, and at small scale on major food production areas.[38]

Underutilizing agroecology in NbS implementation may reduce funding for a global food systems transformation. Agroecology is gaining momentum in global policies as a solution to the global food systems transformation[10] and so does the agroecological principle of diversification in agricultural landscapes.[11,12] Despite its promise on higher yields and lower environmental impact than conventional agriculture, research and development related to agroecology has received less than 1% of public agricultural research funding globally.[39] Currently, about 30% of all farms around the world are redesigning their food production system based on agroecological principles.[40] However, NbS underutilize an agroecology perspective leading to disproportionately lower share of funding for transformative agroecology.[40,41] Despite the vastly uneven funding streams of NbS implementation, the funding for NbS strategies adoption is used for reducing the negative impacts of industrial agriculture. For example, many governments, international nongovernmental organizations, and agribusiness primarily allocated the largest share of funding of NbS on contributing to carbon offsets, net-zero schemes, and technical solutions to increase the yield of land use, such as sustainable intensification or smart agriculture.[41] The word "agroecology" is wrongly used by these actors to describe such activities related to NbS implementation by favoring a set practice of agroecology that accords with the industrialized system. Meanwhile, the summary of publications provides evidence that a given type of ecosystem service is enhanced due to implementation of an NbS integrated with agriculture.[26] For instance, by planting additional cover crops or adding green manure in fallow periods, yields can be maximized, and carbon sequestration is also enhanced through cover cropping.[42] However, ample examples of such co-benefits between NbS and agroecology exist in the literature,[26,27] but without calling them NbS and hence, leading to a funding allocation mismatch. If we can correctly recognize the strong and divisive policy options between NbS and agroecology,[38] much of NbS funding can be more effectively used to address the biodiversity-climate twin challenge in agricultural production landscapes.

Furthermore, the integrated effort of NbS and agroecology is limited to support biodiversity or ecosystem services in agricultural landscapes, but the social dimensions like improved livelihoods, healthy diets, and food security are often ignored.[14,35,38] When it comes to specific practices on livelihoods in agricultural landscapes, references to NbS predominantly feature in community conserved areas and capacity-building programs, such as empowerment and capacity building of landless farmers in Mexico.[35] As an example of funding, the US public funding for the 824 sustainable agricultural projects is only 10% ($294 million) of the total Research, Extension, and Economics budget in 2014,[39] but decreased to $70 million in 2023.[43] However, of the total sustainable agricultural funds, only 14% went to the projects on redesigning farming

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systems to support a socio-ecological transformation of the food system based on social dimensions of agroecology.[39] Moreover, by adopting both, NbS and agroecological practices, farmers could increase their income and food production,[27] for instance in Kenya in the "Upper Tana-Nairobi Water Fund[44]", in Columbia in the "Colombia Silvopasture[45]", in California as part of the "Ecosystem Service Marketplace Consortium[46]", and in China's "Qiandao Water Fund[47]". However, on a broader scale, a limited understanding of the concepts of NbS and agroecology often prevents successful implementation and farmer adoption.[41] Thus, a paradigm shift on food systems transformation requires i) integration of NbS and agroecology with a focus on specifically enhancing livelihoods and social benefits, and ii) an awareness increase to aid practical implementation.

Mismatch of agroecology with advanced technologies

The second is the mismatch of agroecology implementations with advanced technologies, which consequently reduces technology adoption where agroecological practices are used. Agroecological farming practices are aiming to produce yields by utilizing ecological processes and ecosystem services rather than relying on external inputs of synthetic pesticides and chemical fertilizers or in most parts' technological advancements.[17] Agroecological farming practices as an alternative paradigm to conventional agriculture are not anti-technology per se, but rather are guided by a set of principles that are intended to support ecological, more resilient, and equitable food systems.[9,28,29] Indeed, many technologies such as harvesting robots or drone-based pesticide and fertilizer application are initially designed for intensified and highly mechanized agricultural systems.[16] Although agroecology has a long tense relationship with new technologies,[15] the benefits of agroecological production may multiply if technologies are specifically designed for or at least effectively integrated into agroecological production at the field and landscape level.[7,10]

Technology innovations from the production stage along the supply chain to demand monitoring can advance the process of agroecological transition.[48] For example, in Ghana, the integration of hyperspectral drone and satellite imagery can help agroecology implementation and mitigate environmental impacts of intensive food production through climate risk assessment to facilitate decision-support systems.[49] Robotics and autonomous vehicles can reduce human labor and manage more diverse and complex farms.[50] Conversely, the debates about technology have caused negative consequences on promoting sustainable food production for example in India, where genetically modified crops were not used in agroecological farming system because of their potential implications for bio-safety and food sovereignty.[51] In general, recent reviews highlight that the potential of technology integration with agroecological practices is not effectively matched, because 1) stakeholders have partly generalized that agroecology is not compatible with new technologies[15,16,50,51]; 2) a socioeconomic implementation gap exists in technology adoption whereby innovations do not find their way from the laboratory to the field and in the hands of farmers[52]; and 3) evidence and funding are still insufficient to investigate the long-term co-benefits of agroecology and technology.[53] In the future, it is critical to adapt old and identify new technologies for effective agroecology-based farming and enhance stakeholder awareness that agroecological production and technology adoption provides benefits and is not mutually exclusive.

Currently, technologies must directly generate economic benefits or receive government subsidies, but are rarely designed to be well integrated into agroecological farming practices (but see Librán-Embid et al. 2020[54]). For instance, farmers in the Mekong Delta's An Giang Province, Vietnam, only invest in technology when the backup funds are sufficient so that they can counteract the risk of unexpected increasing agricultural input costs.[55] In addition, agroecological practice demonstration and technology introduction in Africa are only completed in small areas but not widely adopted.[56] Lastly, a lack of project funding results in termination of initiatives such as China's agricultural technology demonstration centers.[53] Overall, co-innovation with farmers, value chain actors, and policy makers require careful economic considerations[28] to develop new technologies and enabling policy environments for an agroecological transition.

Implementation limitation of agricultural diversification

The third discrepancy refers to the implementation potential of agricultural diversification in conventional agricultural systems (i.e., simplified and specialized monocultures with high levels of chemical inputs[29]) to enhance multiple ecosystem services without compromising yield. These simplified and specialized agricultural systems create less employment opportunities and are nutrient decoupled with depauperated biodiversity.[18] The number of farmers that can support their livelihoods with agricultural production is substantially reduced, as large-scale production has concentrated a large amount of land on a few family farms.[21] An example of environmental impact of these conventional or simplified agricultural systems is the highly mechanized soy production in monocultures in Brazil, which has led to substantial deforestation and biodiversity loss.[57]

Certified organic agriculture has been claimed to be a sustainable alternative to conventional agriculture since the 1960s.[58] One of the fundamental differences between organic and conventional agriculture is that organic farms do not use synthetic fertilizers, instead relying on compost, animal dung, and other biological nutrition sources.[49] However, by banning the use of synthetic agrochemicals, organic farming leads to biodiversity benefits, but also higher land requirements compared to conventional practices to produce similar yields.[12,49] Critics argued that expanding organic agriculture on a large scale will threaten natural resources and fail to feed a growing human population due to low production efficiency.[25] Furthermore, there are also significant limitations of certified organic agriculture in terms of the biodiversity benefits, when these are measured on a per unit land for similar yield in conventional agriculture systems.[12] Various aspects of agricultural diversification are integrated into organic agriculture and must be more broadly used in conventional farming systems to synergistically pursue production efficiency and biodiversity-based ecosystem service enhancement.

Various diversification practices such as increasing crop diversity (e.g., crop rotation and intercropping) or increasing non-crop diversity around and within fields (e.g., hedgerows, flower strips, and seminatural habitats) can improve ecosystems services, functional biodiversity, and food production.[59] Specifically, in global crop production, pest control, pollination, and biodiversity can be enhanced by respective 23%, 32%, and 40% without yield losses.[11] Switching from organic agriculture to diversified farming practices increases local arthropod richness from 18% to 23% and promotes ecosystem service provisioning stability.[60] Increased landscape diversification in conventional agriculture has also been shown to increase both bumblebee colony weight and densities 3-fold and subsequently crop yields through pollination.[11] Moreover, diversifying cropping systems is a critical step in benefitting from biodiversity-related ecosystem services such as biological pest control. In the case of diversified rice paddies through flower strips, rice yields could be increased and pesticide use reduced in four countries.[61] Thus, diversification has high potential to enhance production capabilities in conventional agricultural systems (for in depth reviews on the topics see[11,12]), once diversification is mainstreamed in the public opinion.

ENHANCED STAKEHOLDER AWARENESS AS A KEY SOLUTION

Stakeholders across agricultural value chains are now promoting a sustainable food system transformation to address major challenges related to agricultural system design such as increasing environmental pressure and climate change. Besides efforts on increasing eco-efficiency and promoting input substitution processes, attention has been increasingly focused on the redesign of agricultural systems across levels of new equipment or plant cultivar design, cropping techniques, and cropping systems in multifunctional landscapes.[6,28,62,63] Although much has been discussed about maximizing both favorable environmental and agricultural outcomes, an increased stakeholder awareness will improve the above discrepancies related to NbS, agroecology, technology, and limitations of diversification implementation that may at least accelerate a sustainable food systems transformation. While the quantity and complexity of stakeholders participating in the transformation of sustainable food system varies, the involvement of both public and private sector actors, such as civil society organizations, food producers, processors, retailers, and consumer organizations is critical.[64]

An integrated dialog model to convince the public for NbS in agriculture

As NbS have gained recognition among civil society, the business sector, and practitioners as a policy tool,[13] bridging the gap between theory and practice is highly relying on enhanced stakeholder awareness in the broader public. A solution needs to demonstrate how NbS help to address complex challenges caused by agricultural production and minimize a low socioeconomic and ecological risk for smallholders and the environment.[38] Besides data to quantify effectiveness of NbS, economic benefits of NbS in agriculture must be clear for all stakeholders.[27] Furthermore, enhanced awareness requires effective communication between stakeholders. A new communication paradigm shift is needed to transform from top-down to an integrated dialog communication model to convince the public with various perspectives.[65] More specially, different groups can prioritize or perceive the advantages (or disadvantages) of NbS in agriculture at various scales from field-farm-farmer to landscape-ecosystem-community scales.[26,27] We therefore recommend the benefits of NbS across two scales should be more explicitly promoted into the integrated dialog model: the temporal and spatial scale. For example, grass or flower strips can create *in situ* benefits for farmers' income and crop yield, but also wider *ex situ* and longer-lasting effects, such as biodiversity, ecosystems services, and the reduction of pollutants in a river, which will be manifested farther downstream.[38] Lastly, NbS must be understood and advertised as practices that are relevant to change agricultural production systems to get corporate and public funding for which effective strategies are still lacking. As agroecology is essentially a NbS, the latter can be discussed alongside traditional farming practices and directly reaching the agricultural community, to gradually help farmers, value chains, and policy makers to understand NbS and then "mainstream" it into large-scale agriculture landscapes.

Enhancing farmer's awareness for coupled innovated technology with agroecology

Agroecological farming can be an economically viable option and create more employment per hectare for farmers,[66] but a broad uptake of technologies such as new crop varieties requires an enabling environment and better understanding among stakeholders. For example, CRISPR-Cas9 gene editing technology can make crop varieties more resilient to climate impacts and pest outbreaks. However, implementation of new genome-edited varieties in the field can be difficult when smallholder farmers have made long-term investments in tree crops such as cocoa, coffee, or citrus.[52] Careful consideration of farmer empowerment and interdisciplinary collaborations are key to prepare agroecological farming practices and enable the use of rather than creating conflict with technologies. The increased farmers' awareness of agroecology involves efforts on economically, socially, and environmentally associated cost-benefit analyses of agroecological farming practices, and on the effects of agroecology on parameters relevant to farmers, value chains, and policy makers.[11] The aim is to further explore the economic vs. environmental trade-off that farmers may face as they transition away from unsustainable and intensive farming practices. This will then provide policy makers with insights into how to create incentive structures to increase the adoption of sustainable farming practices.[67] But to provide practical guidelines for innovative strategies at different scales, three points should be more explicitly solved: 1) integrate new cropping techniques into wider agricultural systems in a long process across scales,[68] 2) initiate a dialog between the agriculture and food scientific communities to avoid limiting their ability to enhance the emergence of effective innovations,[69] and 3) develop technical, market-, and policy-based solutions to enhance farmers' understanding to what extent agroecology and technology makes sense for field actors.[67] Furthermore, while a lot of efforts focus on the landscape scale, finance and knowledge transfer efforts for technology implementation with farmers may need to target the farm scale first.[70]

In addition to enhancing stakeholder awareness of promoting technology integration into agroecological production, we showed in a case study of cultured meat how technology promotes sustainable food system transformation. We argue that stakeholders need to be sensitized for instance for alternative protein sources[7,48] from fermentation-derived microbial protein, cultured meat, or insects (Figure 2). The latter can provide efficient proteins and a beneficial carbon footprint,[72,74] but eating insects is strongly dependent on cultural background and creates moral conundrums in much of Europe and North America.[74] In addition, cultured meat is a new alternative protein source, created in the laboratory without animal involvement,[7] but with an advanced nutritional profile to improve human health while reducing environment impacts. The three main benefits of cultured meat are sustainability, animal welfare, and public health.[71] For instance, when comparing cultured meat to conventionally meat, the former contains higher poly-unsaturated fatty acids and protein content but energy use, GHG emissions, land use, and freshwater use are lower by up to 45%, 96%, 99%, and 96%, respectively.[72] Currently, there is an implementation gap to mainstream controlled and sustainable manufacture of cultured meat in the market (Figure 2). This is, because using food substitutes to abrupt change in consumers' dietary habits may cause unpredictable effects: For example, large-scale production of meat-like products can have a substantial impact on the conventional livestock market.[48] Therefore, it is critical to simultaneously improve technologies to promote conventional food production in a sustainable way and to avoid affecting farmers' livelihoods for a holistic food systems transformation.[7]

Demonstrating possible economic benefit for agricultural diversification over time and in conjunction with technology innovations

Agricultural diversification must be broadly implemented in conventional and simplified agriculture, because diversification can reduce extra inputs by relying primarily on ecosystem functions.[12,18] However, the challenge to align conventional agriculture with diversification is immense, because of the agricultural development paradigm driven by industrialization, short-term productivity, and economic

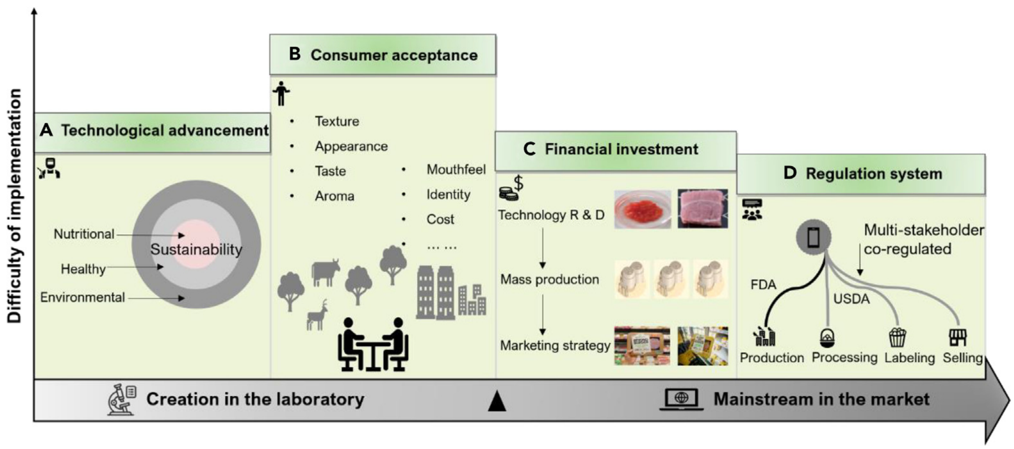

Figure 2. An overview of the technical and socioeconomic implementation gap on cultured meat.
(A) Technological advancements in cultured meat are receiving much attention, including nutritional profile, health properties, and environmental aspects[71] (A). Many factors, such as taste, appearance, cost, and even the relationship between consumption mode and identity, must be fully considered to mainstream these food substitutes.
(B) All these are closely related to the level of public acceptance, because the artificial nature of the product goes against the growing demand for natural and artisanal food (B).
(C) Financial investment in technology R & D at the laboratory level and mass production for decreasing production cost, and marketing strategies at the market level will be crucial to bridge the gap between the science of cultured meat and public perceptions[72] (C).
(D) To eliminate any health and safety risks for consumers, besides the current joint supervision of the US Food and Drug Administration and the United States Department of Agriculture,[73] it also needs open communication and engagement with all stakeholders to ensure that novel food substitutes meet safety standards in every food-related link before being marketed (D).

benefits. For decades, technology-driven intensification has enabled conventional and industrial farms to realize higher incomes than those in agroecological principles.[18,75] Producers trap in an "organic treadmill", driven by specialized market forces, and they have no choice but to replace diversification practices with a set of organic "technology packages" to make the farming system intensive and highly productive.[76] Barriers to producers, especially smallholder farmers, adopting agricultural diversification to this major transformation include lack of information and knowledge, existing policies, strong vested interests in the industrial model, and other economic challenges, such as up-front costs, access to appropriate equipment, and farming infrastructure.[11] These barriers to producers may be removed or at least lowered by the following strategies: 1) Adopting a new decentralized extension approach for agricultural diversification to increase farm income and leading to a win-win solution between economic and ecological aspects.[75] Currently, a decentralized extension approach works effectively, for example, in India whereby the focus is changed from single producer to organizing farmer collectives with an emphasis on agricultural diversification to increase farm income and rural employment[77]; 2) integrating agricultural diversification with technology innovations in national major agricultural policies from the farm to landscape and territory level[18]; and 3) providing financial support to reduce economic burdens on and bridging knowledge gaps to improve diversification farming practices for farmers.[11]

Multi-stakeholder collaborations to encourage farmers for green production

Farmer-focused benefits will be a key solution to enhance environmental awareness at the producer level (Figure 3). Farmers are usually seen as rational economic agents who seek to maximize the economic impact and their adoption behavior depends mainly on whether diversification practices can bring them a superior economic return now or in the near future. Besides economic profit as a driver affecting framers' decision, social-cultural factors such as being perceived as large-scale modern farmers or moral concerns about environmental issues are also major motivations for the adoption of sustainable farming practices.[28] This requires multi-stakeholder efforts by experts, farmer organizations, financial institutions, the market, and governments to focus on farmer benefits, to solve farmers' socioeconomic concerns, and enhance their awareness on environmental issues. Besides the efforts from experts and farmer organization on the

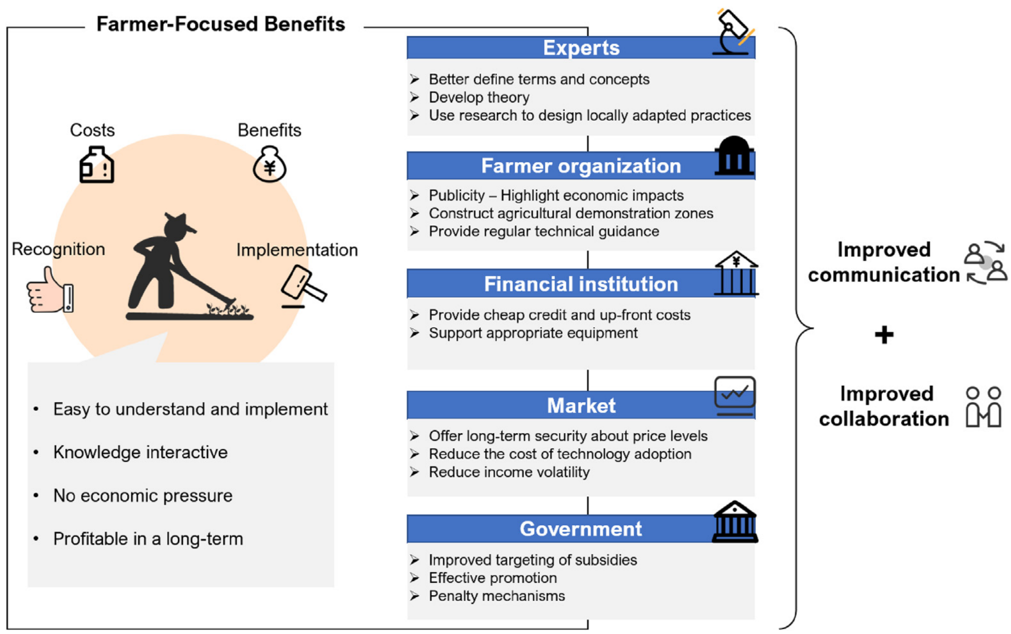

Figure 3. The framework of farmer-focused benefits for enhancing farmer awareness

development and spread of evidence-based knowledge to show the economic benefits of diversification practices, strong and regular technical support also plays a crucial role in the knowledge spread of agricultural practice.[66] The availability of cheap credit, up-front costs, and appropriate equipment is helpful for farmers to remove the economic barriers.[11] Furthermore, offering long-term security about price levels is needed for increasing the incentive for farmers to adopt agroecological techniques as changes of market conditions causing income volatility.[75] Government incentives mainly include subsidies, publicity, and penalties, among which penalties play an "alerting" role in non-compliant production of farmers by increasing the food production cost, and then promote farmers to green production.[78]

OUTLOOK

We argue how increased awareness of agroecology, applying diversification farming practices to conventional agriculture, and increased stakeholder awareness of technologies pave the way for a sustainable food system in the 21st century. In addition to the integration of agroecological principles to modify farming practices as a key step,[9] changes in perception, norms, and values of agriculture are inevitable for all actors along the entire food supply chain. Innovative angles are needed such as going beyond market-driven sustainability standards, whereby the consumer is actively choosing sustainable over conventional products.[10] By defining the best practice in the whole food supply chain from production to the consumption of goods, sustainability standards are typically adopted voluntarily where consumers show a high willingness to pay higher prices for the certified products.[79] Advertisement is an important avenue where environmental topics and sustainability of products can be emphasized and consumer awareness of these topics can be changed subconsciously.[80] There is an urgent need for policy and funding mechanisms that include NbS related to agriculture and enable scientists, farmers, and the public in advancing agroecological farming practices. All of these awareness enhancing strategies will help and are ultimately critical to support the UNFSS's call to action and the transformation to a sustainable food production system.

SUPPLEMENTAL INFORMATION

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S.Z.: Conceptualization, Writing; J.L.: Rewriting, Review, Validation; T.C.W.: Conceptualization, Rewriting-review, Editing, Supervision, Funding acquisition.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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