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Will Sustainable Food Sovereignty Research Be Sustainable in the Future?

Teck Choon Teo

School of Business, TMC Institute, Tashkent, Uzbekistan
Email: teo.john@tmci.uz

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Abstract

The article proposes two agricultural paradigms to address global food production sustainability. First, precision agroecology may unite production-oriented and ecological agriculture, but it offers distinct solutions based on data, innovation, and decision-analysis technologies. The author demonstrates how precision technology and agroecological principles can transform agriculture by 1) minimizing inputs with optimization prescriptions, 2) replacing self-sustaining inputs with location variable rate technology, 3) integrating functional ecosystems into agroecosystems with exact preservation technology, 4) hooking up farmers and consumers via value-based food ecosystems, and 5) establishing equitable agroecology. Hence, precision agroecology provides a rare opportunity to integrate indigenous practices and contemporary technologies to revolutionize farming practices. Precision agroecology can tackle agriculture's most serious sustainability issues in a world in flux.

Keywords

Precision Agriculture, Agroecology, Biodiversity, Food Systems

1. Introduction

As a critical contributor to the problem and a possible remedy, agriculture has considerable responsibility for the state of the environment today. The outputs of today's industrialized farms have increased over time, but at a tremendous expense to nature. Even though modern industrial agriculture contributes to ecological concerns like nutrient pollution, soil depletion, and the destruction of habitats, the increased data access and analysis provided by the industry can address, instead of propagate, issues in crop production. Agri-food systems should be encouraged in the longer term for agriculture since they are productive, commercially prosperous, morally equitable, and ecologically responsible [1].

Humans have long understood that sustainable crop output farming is essential to sustain and nourish the growing global population. Many strategies are being investigated towards this end, including modifications to land use management, the reduction of organic yield gaps, and the introduction of new dietary habits [2] [3]. As a result of these investigations, the author has uncovered two prevailing paradigms that provide alternative approaches to the issues plaguing contemporary agriculture (**Figure 1**). The production-oriented paradigm envisions a range of potential solutions by focusing on output, technological advancements, and efficient resource allocation. At its extreme, the dread of "big data," "agribusiness," and "robot agriculture" discourages most collaborators and practitioners from adopting these modernized food production approaches [4]. On the other hand, the ecological agriculture movement advocates for a more holistic approach to farming that prioritizes ecological solutions and conservation [5] [6]. Others who disagree with the former argue that these movements are short-lived, pointless, and unsupported by science [7] [8]. The author proposes that, despite competing paradigms, profitable and viable agri-food systems can only be achieved through a combination of technological applications and agroecological transformation. In this article, the author defines *precision agroecology* as the practice of agroecology that incorporates the suite of agricultural technologies known as "precision agriculture" (PA) to achieve ecological sustainability.

Precision agriculture often is considered production-oriented. With PA, producers can collect spatiotemporal data about their farms, which they can use to make management decisions to improve output, quality, and sustainability. Most farm technology gathers or communicates with data [9]. Big data analytics in agribusiness is growing as robotics, drones, weather forecasting, and satellite-based

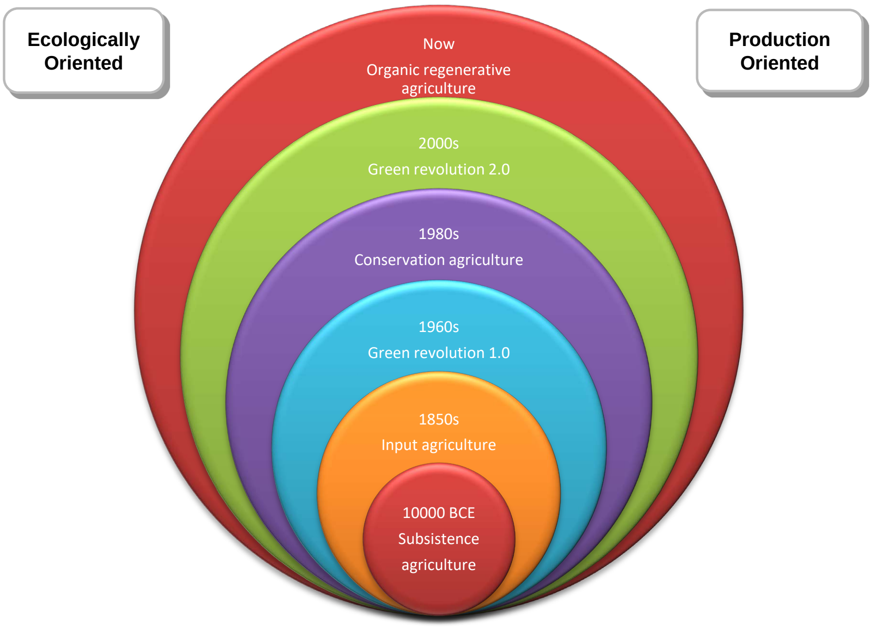

Figure 1. Subsistence farming to industrial and ecologically conscious farming.

data from remote sensing provide meteorological, terrain, and vegetation indicators [10]. Moreover, ground data collection reduces geographical generalizations and informs sub-field-scale management [11] [12] [13] [14]. Precision farming data can significantly improve resource usage efficiency, generate crops that reduce environmental impacts, and promote agroecosystem economic and ecological resilience [15]. In contrast, critics of PA mourn the disappearance of small-scale farming's values, expertise, and data governance. Some worry that PA will make farmers less connected to their land by encouraging them to rely on technology instead of their expertise [16]. Concerns have been raised that it will lead to a continuation of "productivist" principles that put quantity over quality in agriculture and lead to "ecological dystopias" [4]. PA would have the same negative impacts on the environment and human wellness as conventional industrial farming [17]. As a result, PA may be the economic tipping point that leads to the proliferation of megafarms and the eventual replacement of human expertise with automated land preservation efforts.

Conversely, agroecology is a field of study, a management strategy, and a social change that seeks to address environmental and social problems through sustainable agriculture [18]. Applying ecological theories and principles to agricultural systems is the focus of agroecology, a scientific field. Agroecology's indigenous origins mean it does more than apply ecological concepts to boost output and lessen ecological effects; it also tailors those concepts to communities that value the emergence and dissemination of information, cultural and culinary customs, diversification, adaptability, and accountable leadership [19] [20] [21]. To create lasting change in the food system, agroecology considers practices on individual farms and at the regional, national, and international levels. Agroecology also emphasizes local knowledge, helping farmers maintain a personal connection to their land even as new technologies and general recommendations enter the agricultural landscape [22] [23]. Many think agroecology is a fringe movement that can not feed the world because of economic realities and predicted global food demand [24]. In contrast, the author advocates combining these two trends by employing PA technology to oversee agricultural operations following agroecological concepts.

Sustainable agri-food systems, the author contends, require a combination of PA and agroecology rather than their traditional mutually exclusive approaches. Despite their potentially contradictory roots, these two disciplines support viable, fair, and sustainable farming that limits environmental degradation and achieves these goals efficiently. The concept that agroecosystems are intricate and differ significantly over location and time is critical to their integration. Agroecology has yet to be applied to compensate for the unpredictability generated by modest inputs and complicated biological interactions because it can only provide guiding provisions, such as agricultural productivity. In addition, PA provides field-specific information for the establishment of agroecological recommendations. PA is frequently misunderstood as only associated with the "big tech" agriculture area, while it originates in stakeholder-driven research and practice [25] [26]. PA technology and information are critical for establishing on-farm experimentation (OFE) and collective action [27]. In addition, OFE wants to legitimize farmer research on their lands [25]. The advent of PA and other technological advancements has allowed farmers to organize, define, systematically store, and evaluate their trials in previously impossible ways [28]. Most farmers in developed countries can access data-recording tools that track inputs and outputs. However, the agricultural sector still needs to recognize the value of this information in enabling site-specific field management. Management advice can be updated via adaptive management, and on-farm experimentation can be applied, thanks mainly to the vast stream of data via PA sensors and technologies and the availability of extensive archives of open-source satellite imagery. In order to better manage, enhance, and even rebuild agri-food systems, OFE is a cooperative kind of science that draws on farmers' tacit knowledge and data [25] [29].

Advanced innovations are often linked with conventional high-input agriculture, making PA an unusual ally of agroecology at a first impression. However, "farming by soil" [30], was PA's original intention. This means that large-scale farmers could utilize fertilizers across their fields specific to the soil types present, primarily attributable to precise technologies. The original plan called for farmers to take geographical samples of their fields and use the data to create sub-field zones where they could strategically place nutrient applications. Farmers typically apply standard treatments across multiple fields or farms to streamline operations. *Intense farming* is defined as using significant current levels to overcome natural systems' inherent complexity and variability. Nevertheless, PA provides farmers with the technological tools to deal with field complexity [31]. Even though Wendell Berry argued that farmers' use of technology diminished their knowledge of their farms [22], it is possible to envision a future in which farmers will be reintroduced to the intricacy of the ecological relationships on their land because of advances in technology.

Moreover, PA can develop alternative inputs with data. Farmers and scientists use PA technologies, like satellite mapping and combining yield monitors, to obtain site-specific, online information about agri-food processes. Instead of disconnecting producers from their farms, PA should reconnect them to vast fields while offering additional information about the ecological variation within their region [32]. By offering extensive quantitative evaluations of the area and farm size, this method can help enhance farm management and reduce environmental externalities. For instance, by encouraging farmers and markets to regulate and value commodities based on their quality instead of quantity or volume, PA might refocus its agricultural goals away from farm productivity and toward nutrient agribusiness that stresses food quality [33]. Producers should be rewarded for cultivating crops based on nutritional value and optimal control techniques rather than just expected income if agroecology is to achieve its goals in modern agriculture.

Even though agroecology is frequently known as a science, a movement, and a practice [18] [34], the quantifiable aspect of the discipline is frequently neglected, and it should be acknowledged as a framework to yield unbiased scientific knowledge to planning, thus alleviating the deficiency of the experimentation methodology. Agroecology, more usually regarded as a social movement, developed as a reasonable alternative to the intensive agriculture dilemma alongside environmentalism. The social revolutions of the 1990s, which called for a radical shift in farming practices, were deeply linked to the agroecological agriculture systems of the 1980s [35]. The purpose was to create an alternate farming movement to address the agroindustry's societal, economic, and environmental consequences [36]. Agroecology is now a multidisciplinary field that considers agriculture's environmental, social, and economic aspects [37]. Agroecology is a field that uses ecological concepts to guide agricultural practices [38] [39]. These are the adaptive viability, competitive interplay, and crop growth simulations that conventional agronomists and farmers typically ignore [40] [41] [42] [43] [44]. An ecological systems perspective is highly valued in agroecology, as it considers the effects of agriculture on various geographic scales.

In order to develop long-term agricultural solutions, the author contends that PA and agroecology must work together. Although it is based on ecological principles, precision agroecology takes advantage of technological advances and information management tools to expand its scope of observation beyond the field [45]. By bringing together PA and agroecology, it can now achieve breakthroughs in agri-food system design that was previously impossible to achieve. This leads to investigating PA as a viable agricultural strategy for future years.

2. Precision Agroecology: A Five-Stage Framework

Combining these two fields into precision agroecology creates a novel set of agroecological solutions fueled by data collecting, experimenting, and systems for decision-making. In his Agroecology textbook, Stephen Gliessman argued that focusing on increasing crop yields was misguided and that maintaining a functional ecosystem should instead form the basis of agriculture [40]. Although it is critical to meet present food needs and preserve the environment and soil for agricultural production needs, decreasing disparities in food systems on both a local and international level are also essential for agriculture to be sustainable. Producing, processing, distributing, retailing, eating, and the regulatory agencies at each stage are all integral to a food system's ability to function sustainably. Gliessman offers a framework consisting of five stages of transition for shifting from standard industrialized food networks to agroecological approaches that use cutting-edge technology [46]. Precision agroecology helps with the first four stages by 1) enhancing pesticide efficiency, 2) switching to more ecological inputs, 3) optimizing ecological functions, and 4) re-connecting farmers with their customers. The fifth-stage objectives advance past PA's purview and include 5) developing a fair and sustainable global food supply [46]. It demonstrates how PA technology can be implemented within each stage of an agroecological system to realize agroecological ideas and improve the sustainability of the agri-food system (**Table 1**). Finally, the article illustrates how PA approaches can be used across all stages of sustainable transformation. While this article focuses on case studies from stages 1 - 4, the discussion section includes suggestions on integrating PA technology with agroecology at stage 5.

Stage One: Minimizing inputs with optimization prescriptions

The first stage of agroecology emphasizes optimizing pesticide inputs in conventional farming methods. As conflicts between output maximization and pollution reduction are unavoidable, Elliot and Cole advocated for a move toward profit maximization and sustainable crop output [47]. The first step proposed by Gliessman shifts traditional agricultural technology away from suboptimal practices like standardized implementations of chemical pesticides and fertilizer and toward site-specific strategies that significantly improve yields while improving the financial and ecological viability of farming areas [40].

Using PA for site-specific management can boost productivity and help solve problems caused by disproportionate pesticide usage. In locations where crop responsiveness does not lead to greater profitability, precision agriculture lowers input rates to achieve this goal. *Nitrogen fertilizer* is a frequent input that is managed in a site-specific manner. Reduced total nitrogen sprayed over a field and decreased farmer spending on fertilizer are two primary outcomes of reallocating resources from low to high-profit potential locations [48] [49]. The scale at which management units are administered and the procedures used to create prescriptions for site-specific nitrogen management are two of the most significant sources of variation [48] [49] [50] [51]. Research into site-specific fertilizer

Table 1. Framework for precision agroecology.

Stage	Agroecological transformation	Precision agriculture component	Agroecology component
1	Minimizing inputs with optimization prescriptions.	Develop effective prescribes for nitrogen fertilizer, compost, and cover crop treatment at specific sites.	Minimize harmful inputs and consequences to the environment.
2	Replacing self-sustaining inputs with location variable rate technology.	Improve cash crop, cover crop, and animal manure agronomic practices with variable rate technology.	Replace harmful input rates with sustainable, ecological, and location-specific ones.
3	Integrating functional ecosystems into agroecosystems with exact preservation technology.	Employ yield maps and remote sensing to track the ecosystem services provided by non-crop habitat.	Improve ecological integrity and benefits through enhancing diversity.
4	Hooking up farmers and consumers via value-based food ecosystems.	Using production and distribution data, to enhance value-based supply chains.	Create a variety of food networks built around personal connections.
5	Establishing equitable agroecology.	Use the PA data stream to guide policies on every facet of the agriculture and food systems.	Consider the environmental and societal implications of food and farming systems.

applications has been conducted in various agricultural systems across the United States [52] [53] [54] [55]. It has been proven that profit-maximizing site-specific nitrogen management increases financial profits in the grain belt from Oklahoma to Montana [12] [52]. Farmers' net yields can be increased using less nitrogen fertilizer, which also contributes to preserving the natural resource basis on which farming depends. As a result, farmers and the surrounding farming community will benefit financially.

OFE enforced on crop yields is the most effective method for optimizing site-specific control of inputs by allowing farmers to understand crop reactions to variable rate application management consciously. Data collected on farms and through remote sensing must be harnessed to fuel studies and enhance decision-making for site-specific management and OFE. Cloud applications like "MyJohnDeere" and satellite picture archives vis Google Earth Engine [56] make it simpler to collect data from farm devices automatically. Due to its spatiotemporal accessibility, remotely sensed weather predictions or topographical features at harvest data point sub-field sizes can augment any on-farm dataset. Statistical and machine-learning methods can characterize the plant's production (return) and quality response to nitrogen fertilizer inputs and other environmental variables. Once constructed, these models can simulate the results of several complicated management systems. In addition, farmers are given a menu of management options to make their own decisions.

Modern decision support systems, created primarily with maximizing profit theories, have shown promise not only in increasing farmer financial profits but in reducing the quantities of chemical inputs inside farms. Shortly, OFE will play a role in influencing the creation of models that simultaneously maximize revenues and minimize environmental impact. To harness the potential of PA and tackle sustainability concerns in both the economy and the environment, the author proposes a precision agroecological strategy that uses an agroecological perspective to optimize competing goals at each site. While improving chemical efficiency is an essential first step in transitioning industrial agriculture to an agroecological framework, it cannot stand alone as a final destination where agroecology is adapted to fit within conventional farming methods [21]. The idea behind agroecology was to replace synthetic industrial inputs with knowledge of natural interactions. The necessary information is available now, allowing everyone to implement the change.

Stage Two: Replacing self-sustaining inputs with location variable rate technology

In the second agroecological stage, knowledge replaces industrial synthetic inputs. PA can help organic farms efficiently switch to more sustainable supplies [57]. As mentioned in stage one, artificial nitrogen and pesticides are the most environmentally destructive industrial and agricultural supplies. Organic agriculture replaces synthetic inputs with animal dung, crop rotation, and specific knowledge [58] [59]. Switching improves nutrition and minimizes nonpoint agricultural pollutants [60]. Where animal dung is limited, beans and hairy vetch provide nitrogen. These plants also minimize weed density by outcompeting and killing weeds [61]. Local knowledge helps organic farmers apply inputs more precisely and on time. Organic systems do not use pesticides or artificial fertilizers; thus, knowing local conditions is more critical. While conventional farmers rely on their experience, organic farmers apply systems thinking to incorporate novel data into their operations [62]. Hence, precision agriculture data management fits their skill set.

Nitrogen deficits and weed pressures diminish organic agriculture yields. PA and OFE can reduce the yield gap [63]. OFE can help organic farmers better manage their crops by quickly identifying temporal and spatial variation patterns. Cash and cover crop seeding rates affect quality, yield, and competitiveness [64] [65] [66] [67]. Organic OFE then employs trial stochastic seeding rates across farms to identify site-specific seeding rates. This technique decreases weed pressure, optimizes yields, and maximizes farmer net return for nitrogen-fixing cover crops and cash crops like wheat or hemp. Weed survey mapping is also valuable for finding the best management tactics. Initial biological OFE studies discovered spatially variable optimum seeding rates outperforming farmer-selected whole-field rates. OFE enables farmers to adjust plant rates to maximize revenues and reduce nutrient losses. OFE educates organic farmers about the land and how organic inputs influence the number of crops and weeds that thrive on it. Local knowledge assists organic farmers in maintaining their farms without artificial ingredients, allowing PA tools to transition from environmentally harmful inputs to natural ones in a sustainable manner.

Stage Three: Integrating functional ecosystems into agroecosystems with exact preservation technology

In the third stage of agroecological transition, agri-food systems are reconfigured to add more variety to ecosystem structure and make it easier for ecosystems to work [46]. Critics say simplified farming systems are "ecological sacrifice zones" that hurt ecosystems [31]. On the other hand, ecosystem function is more complicated in diverse agroecosystems that keep the structure of natural ecosystems. So, they include a lot more ecosystem support for farmers, which is good. Pollination, eating pests, and eating weed seeds are all excellent ecosystem services linked to biodiversity [68] [69] [70] [71] [72]. However, there may be costs, such as more pests' living places, more weeds, and lower yields [73]. Theoretically, maximizing ecological systems in agri-food systems means using agroecological principles like crop rotation, high biomass cropping systems, and building soil fertility [44]. Various plant species are needed for healthy ecosystems and productive agroecosystems. Increased nutrient cycling, improved soil quality, and new homes for beneficial insects are just a few of the environmental benefits [69] [74] [75]. Reduced unit costs, increased crop nutrients, and stable or increased crop yields are only some of the agronomic benefits that these ecosystem services could bring about. Yet, it is problematic for producers to support ecological functions because they are difficult to define and quantify in ecological systems [76] [77]. The author believes that quantitative data collected at a given site using PA technologies may serve as a preservation strategy on farms to enhance ecosystem services and effectively managing tradeoffs in farming production [78]. To facilitate precise conservation and advance towards more diversified agroecosystems [79] [80], PA is a helpful tool.

Precision conservation utilizes spatial factors to regulate agricultural and natural systems [81]. Precision conservation employs profit modeling to locate low-producing areas in agricultural landscapes for non-crop habitats [68]. Farmers have used various conservation strategies, with some emphasizing the protection of individual species, others on ecosystem management, and others highlighting remnant habitats such as buffer zones and roadside margins. Yet, ecological sanctuaries can also serve as nature reserves, albeit with a more narrow focus. Uncultivated places also called "ecological refugia", are essential for the survival of biodiversity, beneficial insects, and farmers [75] [82] [83]. In addition, the environmental habitat may be natural or restored low-producing zones, including uncultivated riparian habitats, rocky patches, cover crops, or pollinator strips.

It is essential to quantify the economic and environmental benefits of using refugia in agricultural output to encourage their adoption by farmers. Refugia must boost crop productivity and biodiversity; moreover, PA technology enables profit maps, a helpful farm management tool. Yearly profit maps can assess agricultural output and protein content due to refugia distance to evaluate the impact of environmental refugia on agricultural production. Beneficial ecological systems may boost yields of crops or nutritional composition near refugia relative to other fields. Precision conservation eliminates low-yielding regions, saving farmers time and money. This should increase their investment return and restore biodiversity and ecosystem services over the agroecosystem [76]. Since remotely sensed data cannot identify species, biodiversity studies are needed to evaluate plant, insect, and small animal diversity around refugia. But new developments in entomological radar make it possible for sensors to track and control the number and activity of insects by using wingbeat frequency, color, and the ratio of the wing to body [84]. Near-infrared spectroscopy can currently detect sagebrush at the species (75% - 96%) and subspecies (99%) levels, which has significant ramifications for monitoring vegetative remotely over larger areas and more extended periods [85].

Precision agroecology uses PA data and sustainable farming concepts to increase production system ecosystem diversity. Precision technology and sustainable farming management can promote biodiversity, ecosystem stability, and ecosystem function. As a result, PA's growing innovation and ground data collection can assist in determining if ecological refugia support biodiversity, ecological processes, or agricultural cultivation and viability. In addition, precision agroecology will reduce adoption obstacles and allow farmers to participate in agro-based initiatives that compensate farmers for biodiversity in farmscapes [86].

Stage Four: Hooking up farmers and consumers via value-based food ecosystems

As Gliessman argues, the fourth stage of food system reform should focus on accommodating a more significant linkage between farmers and consumers [46]. Entrepreneurs' increasing interest and engagement in providing their communities with locally grown food is a prime example of this aim being achieved. Restoring producer-consumer relationships by investing in LRFSs (local/regional food systems) and encouraging "food citizenship" is one way to stand up to this accusation.

Unlike typical supply chains for farming, an LRFS is a value systems supply chain that pays farmers price rewards for their products' social, environmental, and economic qualities [87]. Hence, value systems supply chains must be transparent and share information at every stage [87]. Value systems supply chains reward food quality, effective management processes, and open data flows to inform customers. Because PA technology enables farmers to share plenty of free, site-specific data with consumers, data on farming systems and nutritional quality food that consumers are ready to pay for could transform value-system supply chains. When given verifiable quality and safety codes, consumers are both "quality-focused" and "price-sensitive" [88]. Evaluations of customer purchase behavior can reveal food nutritional and quality opinions [89]. The PA data stream can be augmented by designating production steps with QR codes to improve traceability. Several manufacturers now utilize the Square app to connect with customers face-to-face reducing data flow. Connecting producers and customers of all sizes are now possible with data-intensive packaging and software solutions.

Conventional farming systems, defined by mass manufacturing, consolidations, and stringent input and environmental laws, are less integrated with their local ecosystem and social hierarchies than LRFSs. As a result, customers and businesses value human rights that pursue ecological and social benefits across the system. LRFSs give consumers food citizenship, and in the food supply chain, a citizen has privileges, obligations, and duties. To develop food citizenship, data and ideas moving through a food supply chain and its value systems distribution networks must be freely available to every stakeholder, from producer to consumer. Food citizenship includes rebuilding consumer and producer faith in credibility foods. Because food supply chain information could be better, producers and consumers alike take a risk on credibility commodities because of customer uncertainty about affordable pricing values and producer confusion about tradeoffs involving certifying prices and cost premiums. It is noteworthy that regulated third-party verification that justifies production adherence and consumer buy-in can generate trust [90]. Third-party supervision necessitates food production with a value systems distribution network, dependable information flows, and sufficient credibility for goods labeling.

Because LRFSs are spreading and multiplying naturally, they might be unstable systems whose behavior is little known at the system level. Using a precise agroecological lens, it is possible to construct a theoretical foundation for LRFSs. Assessment may contribute to preliminary concept, refinement, or substantial restructuring to enhance replication and durability. Spatial and temporal modeling methods may be among the precise instruments for elements of the organizational and social domains where LRFSs occur. Precursor graphical representation simulations of food production can reveal significant features of the system's structure and linkages [91]. Success and failure variables can be identified by parameterizing models using financial, production, ecological, and societal data and simulating LRFSs. Such a strategy would add information accuracy to the construction and management of LRFSs. Diagrammatic models and computational model results, for example, help teach all LRFS participants about system components and the movement of products, services, and data throughout the system. Thus, PA can reestablish farmer connections by bolstering LRFSs, reasserting trust in credence commodities, and creating an awareness of food citizenship.

3. Discussion

Future farming solutions require the unexpected but necessary combination of sustainable farming concepts and precise technologies. Agroecology is ecological, while PA is production-oriented. Despite its reputation for industrializing agribusiness, the article has shown how PA may be utilized in systems that enable decisions modeled with OFE to educate (and support) stakeholder-driven practices [16] [92]. Accordingly, agroecology is a site-specific, measurable science that complements precise technological management strategies [24] [93]. Precise technologies and agroecological concepts can improve agriculture by decreasing inputs, replacing synthetic with ecological inputs, increasing biodiversity, and connecting farmers and consumers.

PA allows traditional knowledge and new technologies to revolutionize food security and can solve agriculture's most significant sustainability issues. They are contamination, habitat destruction, global warming, rural depopulation, and industrial dominance in the agricultural sector. Stages one, two, and three address significant environmental challenges within the agroecological framework. As mentioned in stages one and two, decreasing hazardous farm fertilizers and replacing chemicals used with natural ones, including green manure cover plants for synthetic nitrogen, can minimize pollution. Artificial nitrogen manufacturing and agricultural applications create significant greenhouse gas emissions [3] [94] and cause ecological damage. Stage one nitrogen fertilizer can help conventionally managed farmers increase efficiency benefits. Stage two's cover crop reduces nitrogen fertilizer use and moves conventional farming practices toward sustainability. PA can help minimize and eliminate pesticides throughout the farmscape. The third-stage example shows how precise agriculture can manage farmscapes to protect critical species and slow biodiversity decline while increasing crop yields. Precision preservation can provide patch biodiversity and ecological processes across the farming grid to support sustainable agriculture's land-sharing strategy [78]. Furthermore, PA minimizes emissions of greenhouse gases and nonpoint source pollution and supports adaptive management to adapt to a changing environment. Algorithms can modify best management practices when farmers practice OFE by gathering and applying data. Crop insurance premiums increase with climate unpredictability to reduce crop failure risk. PA information and customized agricultural production models help measure risk and keep insurance premiums from being too high. Weather and climate patterns also change seed, nutrient, and chemical intake levels. Hence, PA might enhance agroecosystem robustness by confronting climate change-induced unpredictability or ambiguity in organizational results [35].

Precision agroecology can help to solve broader societal concerns by altering food systems using sustainable farming solutions. In agricultural production, corporate domination and increasing company earnings have reduced farmer bottom lines and hindered local producers from obtaining the land, finance, and technological tools they require to flourish. Precision agroecology attempts to counteract this tendency by empowering farmers. Precision agroecology encourages landowners to maintain their data and apply farm management strategies by promoting decision support tools. PA can resist being another weapon used by corporations to dominate farmers by stressing stakeholder participation and empowerment, as pesticide inputs and genetically engineered seeds have. It promises to be an accessible technology adaption for farmers with specific minimal PA capabilities, which many do [95], and its deployment will raise their financial profits and economic endurance. Precision agroecology, as demonstrated by stage four, can strengthen farmer-consumer linkages and LRFSs by enhancing farmer prosperity. Precision agroecology should promote farm owner networks that share information about this novel technology. Academic and farmers alike may see their agroecology efforts undermined by corporations looking to cash in on sustainable agriculture trends [20] [21] [92]. Several precautionary suggestions have been made to direct the transition from production-oriented worldviews to innovative approaches that enhance stakeholder involvement and safeguard farmers' shared wisdom, interests, and participation. Corporations can dominate agroecology movements because PA adoption is challenging. Companies can simplify, automate, and market PA technology to farmers, establishing a financial barrier to farmer adoption. Farmer cooperatives should own algorithms developed in conjunction with academia. For example, government agencies need to be incentivized to make precise agroecology algorithms for information integration without giving patents to the industry's highest bidders. This precision agroecology technique limits corporate influence and directly increases farm productivity to farmers, thereby enhancing their field-specific knowledge and financial and ecological sustainability. Obstacles in education, risk, and demographics impede sustainable agriculture. The constraints of precision agroecology include the following:

- Learning and applying PA technology and new practices.
- Being concerned about investment returns such as time and money, and older.
- More conventional farmers' reluctance to shift.

With economic and climatic uncertainty, farmers of all ethnicities are less inclined to experiment with new methods or innovations. Yet, this pause permits generational shifts to occur. Younger farmers who grew up in the digital era and are more willing to embrace novel concepts are more inclined to embrace technological developments. Moreover, precision agroecology is fragile, with limited adoption, yet it must be ready for generational shifts.

The steep learning curves of PA and agroecology make them challenging to implement. Devices and big data sets in precision agriculture often necessitate familiarity with geolocation, mapping, and data management. Plants, integrated pest management, crop rotation, cover crops, and other activities all play a role in agroecology, necessitating a more sophisticated way of farming. So, when these movements are combined into precision agroecology, substantial barriers to adoption arise due to the necessary new learning. Also, it is unreasonable to expect farmers to be statisticians. Nevertheless, even data scientists are not always able to comprehend the algorithms designed to harness massive volumes of data and produce innovative business solutions. Precision agroecology can be made more accessible and valuable for farmers through improved lines of communication and sophisticated, automated, yet interactive decision support systems. For the farmer to obtain insights into the complicated ecosystem functions that can lead to confusing effects of management measures, the algorithms and data analysis must be freely accessible and developed with feedback from the farmer. Hence, precision agroecology can be a reliable and effective tool for farmers who adopt it since it complements rather than replaces the knowledge of these professionals [96] [97] [98]. Furthermore, by designing apps that exploit accessible online information and dynamic analysis, the need to make a clear relationship between data gathering and selection can be increased.

How can farmers' acceptance of PA be enhanced? Researchers have extensively studied the adoption rates of several PA technologies. However, there is a lack of understanding of the factors influencing farmers' decisions to use these technologies. This study offers a fresh perspective on how producers see the advantages of PA technologies.

First, offer education and assistance: Farmers can receive education and help acquire the necessary skills to utilize PA technology proficiently. Second, illustrate the advantages: Farmers can be presented with the positive aspects of PA through talks, demonstrations, and other programs for outreach. This can facilitate their comprehension of how PA can assist them in attaining their objectives and surmounting their obstacles. Third, customize the strategies: Farmers may be provided with tailored options that are adapted to their requirements and circumstances. Finally, engage in stakeholder collaboration: Farmers can participate in cooperative scientific and technological initiatives that include other interested parties, including researchers, specialists, business leaders, and legislators.

4. Gaps in Research and Prospective Research Directions

To close the existing gap in knowledge, farmers require decision-support tools that can aggregate and analyze data from farms and OFE. The implementation of precision agroecology depends critically on the advancement of such systems [99]. Farmers may easily collect massive amounts of location-specific data using PA technology but still need decision support tools to deploy information (data-driven) management fully [100]. To facilitate sustainable management, businesses and startups have worked hard to create decision support systems like FarmBot, FieldNETAdvisorTM, Adapt-N, FaunaPhotonics, Climate Corporation, and Field to Market [101] [102]. These resources seek to equip farmers to manage and utilize their own or open-source data, allowing them to keep decision-making processes on farms rather than outsourcing them to corporations.

Notwithstanding the inherent "black box" and secrecy of OFE research and recommendations, they must be helpful if implemented on farms. The challenge with OFE is that it must be open, inclusive of farmer knowledge, and simple to deploy, all while requiring sophisticated analysis to analyze various complicated on-farm interactions. However, uncertainty over available information, usefulness, and privacy has caused an enormous study gap regarding stakeholder views toward precision agroecology. This research's primary constraint is the trust gap between the information systems (or technologies) and farmers. Of course, this distrust barrier will slow the spread of the precise technology on which OFE depends. While PA is currently at the center of an IP (intellectual property) rights war, this article failed to highlight several ongoing, modest initiatives to create open-source decision-making tools. To build more just and long-term food sustainability, it is crucial that researchers invest in the development of user-friendly PA technology in the future.

In the future, precision agroecology can deal with the fifth stage of agroecology by establishing an equitable and fair global food system. Transforming the world's food system requires data-driven environmental policy. Policymakers need PA data to create incentives and policies considering social and ecological links in agriculture and food systems. Precision agroecology is particularly well-suited to redirect agricultural systems away from maximizing output and enhancing food quality and the environment. One facet of the social dynamics surrounding food systems is their effect on people's health, and precision agroecology offers a unique chance to alleviate this impact. Precision agroecology may factor in negative externalities using PA technology to support food quality regulation, unlike the industrialized agricultural sector, which helps perpetuate environmental and human health costs. Prioritizing crop quality rather than quantity in subsequent research and policy will incentivize farmers and markets to regulate and price crops based on quality, as measured by nutritional content. Shifting the agricultural sector's focus to environmental sustainability would stimulate better management practices, including compensating farmers for ecosystem services. Finally, precision agroecology can recalibrate agri-food ecosystems in a resilient and ecologically sound way because it places equal priority on the quality of food and the quality of the environment.

5. Conclusion

Precision agroecology, which incorporates commercial agriculture technologies to educate agroecological choices better, answers the challenges of today's industrial farming. It is highly doubtful that agriculture, one of the world's most significant sectors, will suddenly undergo a radical transformation. Using agroecological principles in governmental and farmer decision-making will call for collaborative, coordinated efforts across all levels of agroecology. By utilizing the fast-developing technologies and data created from industrial management strategies like PA, precision agroecology changes the orientation of farming production to promote a more sustainable future. By applying data and analytics, precision agroecology is a middle ground between agriculture's competing camps, bringing together otherwise diametrically opposed viewpoints. With additional OFE and regulatory incentives, precision agroecology can result in information exchange of inputs, preservation of uncropped lands to optimize ecological benefits, and realigning direct farmer-consumer interactions. Therefore, the data acquired through precision agroecological management serves as an asset for influencing strategic decisions at all stages to deliver hitherto impossible solutions for revolutionary agri-food systems. Thus, the article suggests precise agroecology as an essential and practical path to future agricultural sustainability. Finally, precision agroecology provides a chance to shift agriculture to agroecological principles as agriculture evolves in an age of climate concern and scientific innovation.

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Conflicts of Interest

The author declares that there is no conflict of interest.

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