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Review

Farming Approaches for Greater Biodiversity, Livelihoods, and Food Security

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Scientists and policy-makers globally are calling for alternative approaches to conventional intensification of agriculture that enhance ecosystem services provided by biodiversity. The evidence reviewed here suggests that alternative approaches can achieve high crop yields and profits, but the performance of other socioeconomic indicators (as well as long-term trends) is surprisingly poorly documented. Consequently, the implementation of conventional intensification and the discussion of alternative approaches are not based on quantitative evidence of their simultaneous ecological and socioeconomic impacts across the globe. To close this knowledge gap, we propose a participatory assessment framework. Given the impacts of conventional intensification on biodiversity loss and greenhouse gas emissions, such evidence is urgently needed to direct science-policy initiatives, such as the United Nations (UN) 2030 Agenda for Sustainable Development.

Trends

Concerns regarding the ecological footprint of conventionally intensified agriculture are global.

Alternative, more sustainable farming systems must also perform well in both social and economic terms.

The evidence reviewed shows that alternative farming systems can achieve high yields and profits.

However, most studies analyze only one dimension of performance, usually the ecological.

The study of each dimension belongs to different research fields, each with its own idiosyncrasies and vocabulary.

A common experimental and multidimensional framework allows for a participatory assessment of alternative approaches to conventional intensification.

Such assessment can support farmers and policy-makers to achieve greater sustainability.

The Global Need for Sustainable Agriculture

Over the past half-century, there has been both an expansion of agriculture around the world [1] and an increased adoption of conventional intensification (Box 1) through larger fields of monoculture crops and greater **external inputs** (see Glossary), pioneered during the Green revolution [2]. It is expected that demands for **agricultural production** will continue to increase as the human population grows in both size and affluence [1–5]. However, because of the widespread environmental impacts from the conventional intensification of agriculture, there is considerable agreement on the urgent need for a global transition to farming systems that ensure **food security** and **nutrition**, provide social and economic equity, and build and protect the **ecosystem services** on which agriculture depends [4–9]. This has led to the promotion of several alternative approaches (Box 1) that harness, rather than supplement, ecosystem services provided by biodiversity (such as nutrient cycling, pest control, or pollination) to achieve resilient and productive farms [10–13]. These approaches aim to either replace external inputs (such as fertilizers, pesticides, or domesticated pollinators, respectively) with ecosystem services, or search for complementarity or positive interaction (Table 1) [11,14,15]. Numerous global initiatives support these alternatives as foundations for global shifts in agricultural practices (Box 2), such as the UN 2030 Agenda for Sustainable Development [6] and the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) [16,17].

Despite growing interest in the alternative approaches to conventional intensification and analyses of their ecological performance [1,11–13,18], here we show that assessments of their relative social and economic performance are rare and currently insufficient for broader meta-analysis.

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Box 1. Different Modes of Farming Systems

Conventional Intensification

Conventional intensification has led to larger fields of monoculture crops that rely on external inputs, including synthetic fertilizers and pesticides [2]. However, many farming systems exist that do not conform to this trend, having different ecological, social, and economic performance [82]. These include traditional farming approaches [83,84] and others that integrate novel technologies [85]. Given that these alternative approaches have different histories, the terms that people use to classify them overlap.

Diversified Farming

Diversified farming describes farms that integrate several crops and (or) animals in the production system. A diversified farming system is a newer concept [86,87], emphasizing a suite of farming practices that promote agrobiodiversity across scales, regenerating ecosystem services, and reducing the need for external inputs. This concept is closely allied with 'agroecology' and 'ecological intensification', while emphasizing cross-scale diversification as the mechanism for sustainable production.

Sustainable Intensification

Sustainable intensification was originally defined as increasing the crop yield while improving ecological and social conditions [88]. It relied on sustainable practices, such as agroforestry, conservation agriculture, and biological pest control (Box 2), to establish low-input 'resource-conserving systems' that are based on promoting favorable ecological interactions within the agroecosystem, rather than depending on external inputs. These approaches were found to improve yields and livelihoods in developing nations [43]. However, recent usage has shifted the focus toward capital and external input intensive solutions to enhance resource-use efficiencies, such as irrigation, precision agriculture, fertilizer application, and genetically modified organisms (GMOs) [89], leading to criticism that the concept no longer promotes social equity [7,39].

Ecological Intensification

Ecological intensification describes a process rather than an end point. It provides one path toward higher crop yield that fits within the original sense of sustainable intensification. Ecological intensification emphasizes management to enhance ecological processes that support production, including biotic pest regulation, nutrient cycling, and pollination; there is an explicit focus on conserving and using functional biodiversity [11]. The result is a farm that is likely to meet the definition of a diversified farming system.

Agroecological Farming

Agroecological farming is knowledge, management, and labor-intensive rather than external input-intensive, and aims to regenerate long-term agroecosystem properties by incorporating functional biodiversity [28], leading to sustainable, resilient systems [90]. Agroecological methods are often rooted in traditional farming practices and (or) are co-developed by farmers and scientists with the aim to enhance food sovereignty [83].

Organic Farming

Organic farming originated as a holistic system for enhancing soil fertility, water storage, and the biological control of crop pests and diseases [12,91] and was traditionally associated with low-input, small-scale, diversified farms. A more recent development, certified organic farming, prohibits the use of most synthetic inputs and GMOs, while allowing organic fertilizers and pesticides [12]. Many organic farms today practice 'input substitution' and so, similar to conventional farms, they are high input, occur on a large scale, and sustain low-crop and noncrop diversity, but use permitted organic products instead of synthetic fertilizers and pesticides [87,92]. Thus, today, organic agriculture includes a wide spectrum of farming styles.

There are few peer-reviewed assessments [19–22], with most evidence coming from case studies or gray literature. Furthermore, the integration of ecological and socioeconomic evidence is challenging because the multiple disciplines involved have different traditions and vocabularies [23]. Therefore, here we: (i) briefly review the limitations of conventional farming systems, including discussion of why food security is not being solved by higher **crop yields** alone; (ii) characterize alternative farming systems commonly referred to in the scientific literature; (iii) review literature (and evidence) on the ecological, social, and economic performance of farming systems; and (iv) present prospects for future research, including the need for a standardized methodology that empowers farmers to participate as researchers, to address the lack of quantitative evidence. Throughout, we emphasize that decision making should account for the social and economic consequences of farming systems (Box 1) [10,21,24], recognizing that **agricultural sustainability** will depend on the actions of organizations in government and civil society (hereafter 'policy-makers'), rural communities and land managers (hereafter 'farmers'), researchers and field technicians (hereafter 'researchers') [10,21,24].

Shortfalls of Conventional Intensification

Conventional intensification has been the mainstream strategy for agricultural development for decades [25], but has become a major environmental pressure [12]. The conventional paradigm has been to maximize crop yield, which, some argue, has decreased the rate of agricultural expansion, saving land for natural habitats and other uses [15,26]. Another possibility is that an increase in crop yield augments the **profitability** of land conversion and leads to further agricultural expansion [27–30]. Agriculture is considered the driver for around 70% of the projected loss of terrestrial biodiversity globally [31]. Equally, agriculture is a major contributor to greenhouse gas emissions, although there is disagreement to the extent of this contribution, with estimates ranging from 10% to 45% of global anthropogenic emissions [32–34]. Moreover, the current demands from agriculture on the freshwater resources of the world, in addition to desertification, salinization, soil erosion, and other consequences of unsustainable management, are of major concern [4,5,12].

From a socioeconomic perspective, it is often argued that the greater crop yields achieved by conventional intensification were essential to improve food security, with further yield increases necessary to feed a growing population [5,15,35]. However, there are stagnating or declining yield trends in many regions where conventional intensification has been applied [36]. In reality, although global agriculture produces more than enough food to feed the current human population, around 800 million people are chronically undernourished (2012–2014), and **food production** in many regions of high food insecurity remain at the same levels they were during the 1960s [9,13,37]. At the same time, global levels of obesity have more than doubled since 1980: more than 1.9 billion adults were overweight in 2014 and, of these, over 600 million were obese [38]. Including both the overweight and undernourishned, around 3.3 billion people suffer from malnutrition, representing more than 45% of the human population (Figure 1).

Malnutrition has occurred because greater crop yields do not necessarily result in improved **food availability**, **access**, and **utilization**, all of which are critical aspects of food security (Figure 1) [7,39–41]. Moreover, the commonly proposed strategies to improve food security, such as closing yield gaps, increasing production limits, reducing waste, and eating less meat, focus on improving food availability rather than on access or utilization [5]. Despite a widely acknowledged need for production to address the breadth of human dietary requirements, a few energy-dense cereals (maize, wheat, and rice) and livestock fodder crops, such as soybeans, have grown to dominate global agriculture. At the same time, vitamin deficiency remains a problem in many regions [8,42]. As such, in many parts of the world, conventional intensification has not met with the rates of adoption anticipated considering the levels of investment in its research and dissemination; neither have conventional approaches necessarily achieved food security and adequate nutrition [3,4,8,9,13,24].

Moving Towards Alternatives to Conventional Intensification

In recent decades, several alternative farming systems (Box 1) have been proposed by researchers and policy-makers with the aim of supporting crop yield while addressing some of the issues in conventional intensification. These alternatives generally recognize that farming systems include ecological, social, and economic dimensions (Box 1, Table 1) [10,12,19,24]. Ecologically, they can be designed to harness biodiversity and optimize the ecosystem services that underpin agricultural production, resulting in regenerative systems that are less dependent upon external inputs and create fewer negative **externalities** [12]. For example, practices such as agroforestry, aquaculture, conservation tillage, integrated nutrient management, integrated pest management, crop–livestock integration, and water harvesting have been successfully applied in many developing countries [43] (Box 2). Socially, farming has largely been carried out by families and communities and, even today, **family farms** represent 98% of farms globally [44]. Some alternative approaches (Box 1) aim to increase local development and **food**

Glossary

Agricultural production: amount of crop output (e.g., tons), including food (e.g., wheat) and nonfood (e.g., cotton) products.

Agricultural sustainability: 'Sustainability in agricultural systems incorporates concepts of both resilience (the capacity of systems to buffer shocks and stresses) and persistence (the capacity of systems to continue over long periods), and addresses many wider economic, social and environmental outcomes' [2]. See also [18] for more discussion.

Crop yield: a measure of agricultural productivity expressed as the amount of crop output (e.g., tons) given a certain area (e.g., hectares) and during a certain period (usually a crop cycle or one season).

Ecosystem services: direct or indirect benefits to human wellbeing provided by ecosystems, such as nutrients for crops naturally available through nutrient cycling. Agricultural management can enhance or degrade ecosystem services [48].

External inputs: subsidies from outside the farming system usually aimed at increasing crop yield or reducing risks, such as insecticides or nutrients supplied through fertilizers.

Externality: a cost (such as an environmental cost) or a benefit (such as an ecosystem service) that affects a party who did not choose to incur that cost or benefit, and is not paid or compensated (negative or positive externality, respectively). The existence of externalities is dependent on the structure of the property rights. For example, biological pest control received freely by a farmer from a nearby natural habitat owned by another farmer is a positive externality, while water contamination received by communities inhabiting lowlands from agrochemical pollution of farmers inhabiting highlands is a negative externality.

Family farm: a farm where the family does the majority of the work and controls their own resources, such as land, crops, livestock seeds, or buildings. The farm generally produces some or all of the food and income of the family. It has less to do with the scale of the farm, although most are small scale [44,96].

sovereignty, recognizing that experienced farmers and empowerment of local communities are the base of sustainable production across varied landscapes [10,19,24]. Economically, farming provides stable income, employment, and livelihood to around 1.3 billion of people (one-third of the economically active labor force of the world) [3,12,24,45], including 70% of the rural poor of the world [46]. Some alternative approaches contrast with conventional intensification in giving a broader recognition for these multiple private and public goods, services, and externalities generated by farms, including diversity and long-term stability of production, resistance and resilience to disturbance, and enhancement of rural livelihoods and cultures [19,24]. However, alternative approaches to conventional farming are often criticized for being too low yielding, labor intensive, or otherwise economically flawed [25,35].

Measuring Effects

Discussion of alternatives to conventional intensification often considers their effects on externalities (increasing positive externalities, such as ecosystem services, and reducing negative externalities, such as biodiversity loss) and public, as well as private benefits [19,24] (Box 3). As highlighted previously, these practices are hypothesized to have positive impacts on several socioeconomic variables, increasing synergies and reducing trade-offs. For example, in systems of irrigated rice fields and fishponds, eliminating pesticides permits diversification through the production of fish and other aquatic organisms, facilitating pest and weed control (Box 2). As another example, increasing the conservation area in a farm could reduce agricultural production because of reduced crop area, causing short-term economic losses [47]. However, it can also generate long-term benefits through higher, more stable crop yield because of stronger ecosystem services (e.g., pollination or pest regulation) [47] and enhance revenues from other income streams (e.g., forest products or tourism). Understanding and quantifying these impacts is crucial to support informed stakeholder decisions, such as understanding the costs and benefits of adopting a practice, identifying opportunities to use these practices more efficiently, or designing instruments to support their adoption. The benefits of ecosystem services or other positive externalities are often measured in monetary terms [12,20,48,49]. Although this makes the impacts simpler to communicate, often substantial assumptions must be made to translate benefits into monetary units, miscommunicating or even neglecting specific noneconomic costs or benefits [50,51]. Furthermore, not all impacts can or should (for ethical reasons) be quantified in monetary terms [17,52], such as serious health impacts.

Evidence of Social and Economic Performance

To explore the available evidence of the socioeconomic impacts of farming systems, we performed a literature review on a subset of human (labor productivity, labor demand, and access of farmers to training or knowledge), financial (crop yield, farm profitability, income stability, recognition or assessment of transition costs), and social (access to the market, number and quality of community groups, and participation of stakeholders in decision making) indicators. We focused on 13 practices common to alternative farming systems (Box 2): aquaculture, biological nitrogen fixation, community governance (participation in forest management), conservation tillage, crop diversification, direct seeding, integrated nutrient management, permanent soil cover, optimal plant spacing, small-scale irrigation, use of compost or organic matter, water harvesting, or water-use efficiency. The full text of the article was reviewed if the abstract referred to at least one of the practices.

We identified 99 papers (Scopus database) that met the keyword search, but of these, only 17 papers [53–69] were found to have quantitative data on the socioeconomic indicators we selected. Although the studies provided 154 comparisons between conventional and alternative practices, they were narrow in scope, most of them addressing crop yield (74 comparisons) or farm profitability (73 comparisons). Interestingly, 61% of the comparisons showed greater crop yield for alternative rather than conventional practices, while 20% found the opposite trend and

Food access: 'covers access by individuals to adequate resources (entitlements) to acquire appropriate foods for a nutritious diet. Entitlements are defined as the set of all those commodity bundles over which a person can establish command given the legal, political, economic, and social arrangements of the community of which he or she is a member. Thus a key element is the purchasing power of consumers and the evolution of real incomes and food prices. However, these resources need not be exclusively monetary but may also include traditional rights, e.g., to a share of common resources' [40].
Food availability: food available for direct human consumption after accounting for other uses of food production (e.g., biofuel or food waste).
Food production: amount of food output (e.g., tons), regardless of its final destination (e.g., includes maize production regardless of whether it is used for human consumption, animal feed, or biofuel production). Food production cannot be equated with food security (Figure 1, main text).
Food security: 'a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life' [9]. Food security is commonly conceptualized as resting on three pillars: availability, access, and utilization. These concepts are inherently hierarchical, with availability necessary but not sufficient to ensure access, which is, in turn, necessary but not sufficient for effective utilization [9,37,40].
Food sovereignty: 'the right of local people to control their own regional and national food systems, including markets, natural resources, food cultures and production modes' [97].
Food utilization: 'encompasses all food safety and quality aspects of nutrition; its subdimensions are therefore related to health, including the sanitary conditions across the entire food chain. It is not enough that someone is getting what appears to be an adequate quantity of food if that person is unable to make use of the food because he or she is always falling sick' [40].
Intensification: a process aimed to increase crop yield. For example, an

19% showed no differences. Similarly, 66% of the comparisons achieved greater farm profitability for alternative than conventional practices, while 11% found the opposite trend and 23% showed no differences. Focusing on those studies that measured both crop yield and farm profitability, alternative practices increased the two indicators simultaneously for 59% of the comparisons. Importantly, we found no trade-offs between farm profitability and crop yield, whereas simultaneous decreases in both indicators were found only in 18% of the comparisons. In agreement, a recent meta-analysis of the financial performance of organic and conventional agriculture indicated that total costs were not significantly different between systems and that price premiums result in greater profits and benefit:cost ratio from organic farming [70]. Overall, these results do not support the assumption that alternatives to conventional practices are low yielding or less profitable [35].

organic farm can start a process of conventional intensification, while a conventional farm can start a process of ecological intensification.
Malnutrition: refers to undernutrition, obesity, and micronutrient (mineral and vitamin) deficiencies [9].
Profitability: the difference between income (usually related to crop yield, quality and price) and costs (e.g., of fertilizers or pesticides).

Table 1. Similarities and Differences among Six Farming Systems Commonly Referred to in the Scientific Literature[a]

	Conventional	Sustainably intensified	Organic	Diversified	Ecologically intensified	Agroecological
Uses synthetic inputs	✓✓✓	✓✓✓	✗✓	✗✓	✗✓	✗✓
Uses GMOs	✓✓	✓	✗✗✗	✗✓	✗✓	✗✗✗
Integration of livestock	✗✓✓	✗✓	✗✓	✓✓✓	✓	✓✓
Uses crop and livestock species diversity	✗✓	✗✓	✓	✓✓✓	✓✓✓	✓✓✓
Encourages nonfarmed species diversity	✗✓✓	✓	✓	✓✓✓	✓✓✓	✓✓✓
Encourages spatial heterogeneity	✗✓	✓	✓	✓✓✓	✓✓✓	✓✓✓
Exploits ecosystem services	✗✓	✓	✓✓	✓✓✓	✓✓✓	✓✓✓
Plans for resilience	✗✓	✓	✓	✓✓✓	✓✓✓	✓✓✓
Exploits processes at multiple temporal and spatial scales	✗✓	✗✓	✗✓	✓✓	✓✓✓	✓
Highly labor dependent	✗✓	✗✓	✓✓	✓✓✓	✓✓✓	✓✓✓
Explicit focus on traditional knowledge	✗✓	✗✓	✓	✓✓✓	✓	✓✓✓

[a] ✗✗✗, never; ✗✓, rarely; ✗✓✓, rarely sometimes; ✓, sometimes; ✓✓, sometimes often; ✓✓✓, often.

Box 2. Examples of Practices Aiming to Reduce the Environmental Impact of Agriculture While Potentially Enhancing Social and Economic Performance

- Aquaculture incorporates fish, shrimp, and other aquatic animals into farm systems, such as irrigated rice fields and fishponds, and so leads to increased protein production [43].
- Crop diversification, such as agroforestry, incorporates multifunctional trees into agricultural systems, and collective management of nearby forest resources [43,87].
- Integrated nutrient management seeks to balance the need to fix nitrogen within farm systems (e.g., biological nitrogen fixation) with the need to import inorganic and organic sources of nutrients (e.g., use of compost or organic matter) and to reduce nutrient losses through erosion control [43].
- Integrated pest management uses ecosystem resilience and diversity for pest, disease, and weed control (biological pest control), and seeks to use pesticides only when other options are ineffective [43].
- Livestock integration into crop systems, such as dairy, cattle and poultry, including using zero-grazing [3,43].
- Permanent soil cover, so that soil can be conserved and available moisture used more efficiently (water-use efficiency). This objective can be achieved by several practices, such as conservation tillage, which reduces the amount of tillage, sometimes to zero, usually associated with direct seeding and optimal plant spacing [43].
- Water harvesting in dryland areas (small-scale irrigation), allowing formerly abandoned and degraded lands to be cultivated, and additional crops to be grown on small patches of irrigated land owing to better rainwater retention [43].

By contrast, we found that the number of comparisons for the other socioeconomic indicators was too low: only four comparisons for labor demand, three comparisons for labor productivity, and none for the other variables. This disparity in the indicators examined highlights a literature bias towards economic impacts rather than the broader impacts of changing agricultural systems on wellbeing. Similarly, despite widespread literature about the pros and cons of organic versus conventional farming systems, most of the socioeconomic evidence relates only to crop yields and profits [12,25,35,70,71]. Part of this might be pragmatic, because yield and profit can be estimated from experimental work alone, while other variables require additional social science analysis.

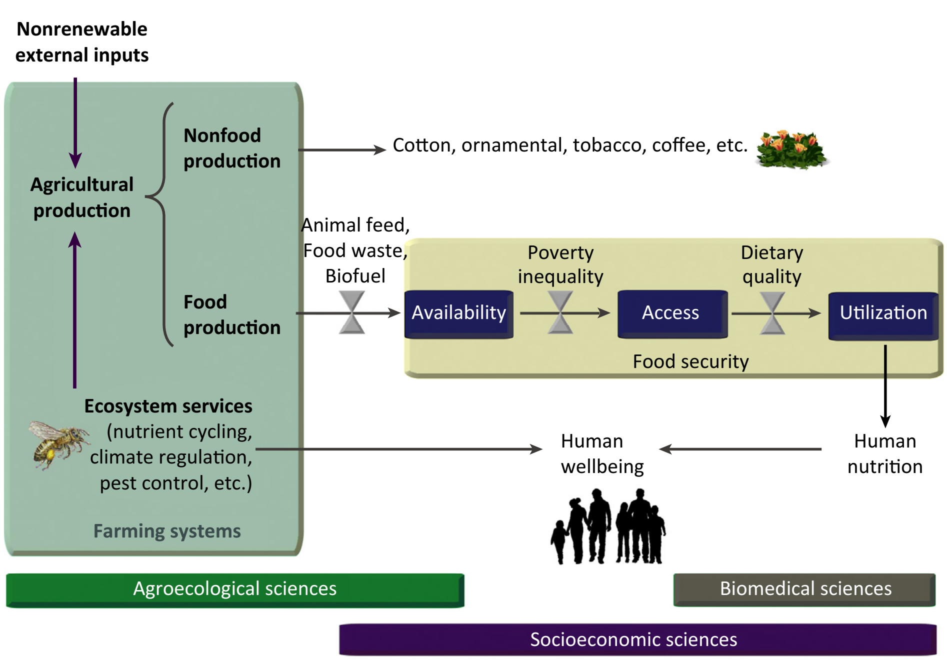

Figure 1. Drivers of Human Nutrition Include Ecological, Social, and Economic Dimensions. Conventional intensification focuses on increasing crop yield through external inputs, which does not necessarily provide greater human nutrition or food security. Alternative approaches should incorporate socioeconomic dimensions to improve food availability, access, and utilization, while enhancing ecosystem services. Examples of key factors affecting food availability, access, and utilization are shown.

Box 3. Integrating the Notion of Value across Ecological, Social, and Economic Sciences

Assessments of performance are usually motivated by the need to improve decision making, which is the process by which agents (farmers, policy-makers, and researchers) choose among decision alternatives (farming systems) according to their values. The literature has a wide spectrum of definitions for the 'value' of farming systems, with different meanings across disciplines [16,17,22,51,52]. The IPBES conceptual framework is based on the general notion of the benefits of nature to people, where a benefit is a perceived thing or experience of value to some aspect of people's quality of life [17]. Thus, value can be considered a quantitative and (or) qualitative expression of the impact that farming systems have on the wellbeing of people (Figure I). Values (i.e., performance measures) are generally quantified by contrasts, such as the comparison of the effects on crop yield of conventional versus alternative farming systems (i.e., marginal values). Marginal values are relevant for decision making because partial changes of benefits are more likely than complete loss, and also because it is at the margin that decisions are made [52]. Each time we make a decision affecting ecological resources, there is an implicit valuation of the consequences of this choice, involving trade-offs with other land-use decisions. Valuation is a process in which these values are made explicit by using well-informed methodologies and criteria [52].

Values can be expressed in monetary and nonmonetary terms at various spatial and temporal levels (e.g., farm, landscape, or regional) [93]. Ecologists usually quantify the performance of farming systems through nonmonetary biophysical variables, such as changes in biodiversity or ecosystem services, while economists usually quantify values in monetary terms [52,81]. The IPBES conceptual framework proposes that pairing different value systems with different valuation approaches and techniques can provide an integrated value map of the benefits of nature [17].

Current markets and economic indicators fail to capture the full range of (current and potential) benefits from farming systems to human wellbeing (e.g., water purification, oxygen production, nutrient recycling, or climate regulation). Given that many decisions on land use are based on markets and economic indicators, such failures can result in the loss of these benefits and land-management decisions that are poor from a social perspective. Indeed, many farming practices can cause increased erosion, salinization, soil compaction, chemical pollution of soil and water, and biodiversity loss, among other symptoms of degradation. Valuation of such benefits provides information to undertake corrective actions.

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Figure I. In Zimbabwe, Organic Polycultures Managed and Marketed by Farming Cooperatives Can Share High Ecological, Social, and Economic Values. Worldwide, scientists are calling for alternative, more sustainable approaches to conventional intensification. However, the simultaneous ecological, social, and economic performance of different farming approaches have not been assessed within a framework that allows for a systematic comparison.

Most of the studies reviewed were from Asia (70%), many focusing on India and China, followed by Americas (18%), Europe (6%), and Africa (6%). Only two studies examined the impacts of alternative practices in developed nations [59,68]. In terms of the farm practices addressed, a large portion (around 40%) of the comparisons involved permanent soil cover, while, for most of the 13 practices, there was no assessment of impacts. Furthermore, most comparisons were not sensitive to changes over time. Given that management might take several years to produce impacts on indicators and, more fundamentally, impact the long-term stability and sustainability of benefits [1–3], this shortcoming severely limits the capacity to compare the sustainability of different farming systems. Finally, 65% of studies examined only a single practice, while 41% of studies included conventional practices mixed with alternative ones. As such, none of the studies truly compared alternative systems with conventional agriculture. Therefore, our review reveals that the socioeconomic performance of agricultural approaches (conventional as well as alternative) is surprisingly poorly documented and lacks a structure relevant to decision making (see also [12,20,70]). Such a limited evidence base severely limits the capacity of policy-making and science to encourage the sustainable agricultural changes advocated.

A Framework for Building an Evidence Base

Our review highlights that only limited, short-term data are available on the socioeconomic impacts of a small number of farming practices. As such, the case supporting any given farming system is heavily dependent upon ecological impacts and indirect evidence that ecosystem services will result in social and economic benefits. Although many frameworks exist to assess sustainability, they usually do not cover the ecological, social, and economic dimensions simultaneously and are difficult to adapt to contrasting local circumstances and different spatial scales [18]. Moreover, because of a lack of standardization and common vocabulary, different frameworks of assessment can give contradictory results, even for the same farming system [18]. Therefore, developing a coherent, flexible, and easily interpreted framework to capture the full range of these benefits is essential. Such a framework will be more useful if it includes a plurality of views (legitimacy) and is relevant to the needs (e.g., income or social identity) of the stakeholders affected (salience) [72]. A participatory approach involving affected stakeholders from the beginning of the process is important to empower and educate [19,73], to take advantage of local knowledge, and to increase the legitimacy of the outcomes [74] (Box 4).

Our framework follows such a participatory approach and includes the following steps (Figure 2). First, a definition of an alternative system and a conventional contrast is agreed. Second, the natural, social, human, financial, economic, and cultural assets that are going to be measured are discussed (Box 3). Participatory methods (e.g., through specific focus groups, workshops, or questionnaires) can be used to decide which measures are most appropriate and correspond to agreed definitions, respecting the knowledge and priorities of stakeholders. To capture these measures, a combination of primary (crop treatments, social science surveys, etc.) and secondary data (local income, market price, etc.) will usually be required (Figure 2). Primary data through standardized protocols will facilitate: (i) comparison between studies; and (ii) meta-analyses of wider impacts [73,75–77]. Data collection can involve stakeholders through, for example, farmer field schools that allow participants to create their own contrasts [75] or platforms such as the Self-evaluation and Holistic Assessment of climate Resilience of farmers and Pastoralists (SHARP) of the Food and Agriculture Organization of the UN (FAO; Box 4). Qualitative approaches will be important to capture social impacts, such as local empowerment and food sovereignty. Gathering primary data usually involves a preliminary sampling to adjust the protocol, in which a set of pilot sites (five to ten) with contrasting systems is identified, and measurement methods (vegetation and crop diversity, soil erosion, etc.), questionnaires, and spreadsheets are developed. Sites must be representative of the size, structure (typical crops

Box 4. Tools to Create Participatory Data in Farming Systems

A variety of tools to assess the sustainability and resilience of farming systems have been reviewed, such as the SAFA and SHARP tools from the FAO (Figure I), Heeks and Opsina's RABIT, CoBRA from the UN Development Programme (UNDP), and Climate Proofing from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) [76,94,95]. These tools incorporate different understandings of sustainability and resilience, and measure those constructs on varying levels and with different approaches. Based on the existing reviews of these frameworks [76,94,95], an effective tool for building the evidence base for farming systems in a participatory way should: (i) be based on a strong theoretical grounding, considering farming systems as integrated socioecological systems; (ii) incorporate ecological, social, and economic aspects of sustainability; (iii) integrate quantitative and qualitative research methods; (iv) foster notions of participation, learning, and empowerment; (v) be a simple, self-assessment tool targeted at the individual or household level, but which considers multiscalar interactions; and (vi) provide data and assessments that allow comparability between sites.

With the goal of creating a place to share, learn, and engage, there are several attributes that would be beneficial. Ideally, the tool would connect farmers to farmers, scientists to scientists, programme managers to programme managers, and between each of these groups. Attributes needed for developing and implementing a knowledge sharing platform are: (i) location: online, but with data and videos downloadable; (ii) user friendly: easily shareable (viewable) and available in multiple languages [73]; (iii) multilayered: providing both an interface that is aimed at sharing information with people on the ground (e.g., farmers), as well as a set of case studies and peer-reviewed articles backing up the information. It is important to provide best practices (e.g., Digital Green through the use of farmer-developed videos); (iv) interactive: providing a space for farmers to comment and discuss among themselves to ask questions and share answers; and (v) visual: a dynamic area that displays geographical and temporal information, such as practices used in different countries and impacts on resilience over time.

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Figure I. Using the SHARP Resilience Self-Assessment with Communities in Sub-Saharan Africa.

grown, typical mix of activities, etc.), and business model (number of people employed, typical machinery used, etc.) of the area. Secondary data, particularly socioeconomic characteristics, can be collected from databases such as FAO statistics or national statistics agencies, ideally focusing on the appropriate region where measures are being tested. However, such data are

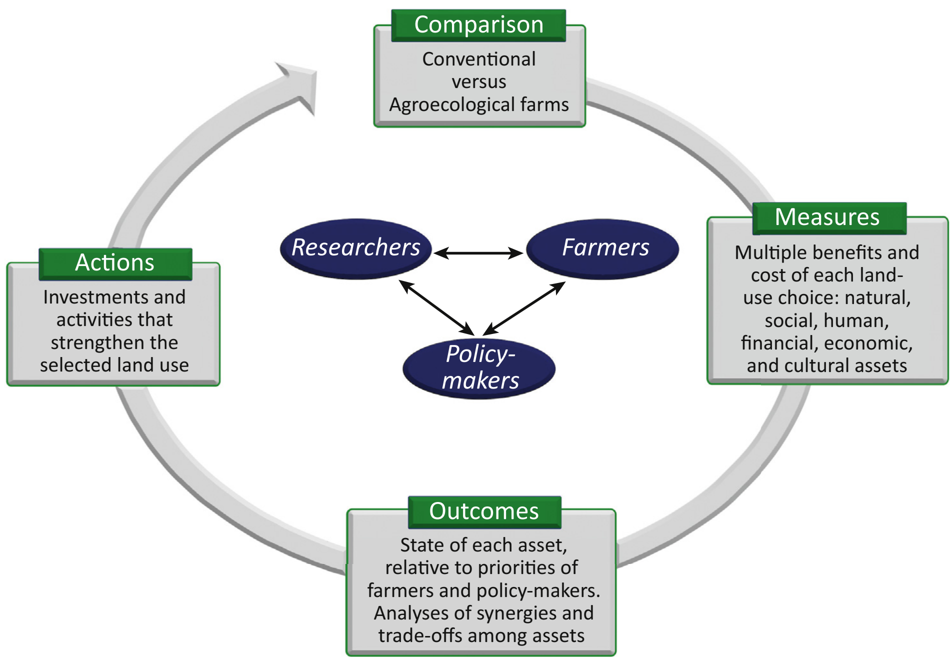

Figure 2. Framework for an Evidence-Based Assessment of the Ecological, Social, and Economic Performance of Farming Systems. Our framework proposes a participatory approach among three groups (blue ovals) in each of four steps (gray boxes). The three groups are policy-makers (i.e., organizations in government and civil society), farmers (i.e., rural communities and land managers), and researchers (i.e., field technicians and researchers). The four steps can be accomplished using field and satellite data, through expert (including farmers and researchers) opinions, or a mixture of both types of information.

often inconsistent or missing, especially in some developing nations, and can be less accurate at local scales, necessitating the use of proxies or additional primary data collection (e.g., more detailed surveys).

Third, data analyses are carried out according to farmer and policy-maker priorities (Figure 2). Data can be analyzed using multivariate statistics [78] or a multicriteria analytical framework [49,79,80]. Multicriteria, cost–benefit analyses would allow for quantitative assessments of a range of trade-offs from alternative practices; however, they remain limited by the lack of widely recognized, easily understood social and ecological metrics [80]. Spider web plots can be used to communicate the impacts on the multiple variables [1,12].

Finally, the evidence would lead to actions that strengthen the selected farming systems (Figure 2), which then need to be monitored in terms of the multiple costs and benefits. Such adaptive management process involves a progressive reanalysis of outcomes from farms where actions have been taken, compared with those maintaining conventional practice. Given that transparency is crucial [72,74], the framework proposes that some measure of uncertainty (e.g., a range of values for each indicator) is included in the assessment of the multiple costs and benefits [81]. Unfortunately, many methods for evaluating the benefits of land-use choices do not adequately capture or express the uncertainties (e.g., the natural variation in benefits or changing demand for foods) within their estimates [51,81]. Uncertainty is further exacerbated by several biological knowledge gaps, such as the interactions between ecosystem services and external inputs [51,81]. These interactions are difficult to quantify and, thus, will require new primary research.

Concluding Remarks

Our review demonstrates that alternative farming approaches can achieve high yields and profits, but evidence of the simultaneous impacts of farming systems on ecological, social, and economic aspects of sustainability are scarce (see Outstanding Questions). The study of each aspect belongs to different research fields, each with its own idiosyncrasies and vocabulary. An increase in the number of studies that use a common framework to quantify these multifaceted impacts would facilitate the finding of 'high-level' patterns to help understand what solutions are most likely to work in which situations, across regional and national lines, and across specific farming systems. Given that the current food system is seen as the driver of many negative impacts on the global environment by both intergovernmental initiatives and the scientific community, priorities need to be established for identifying farming systems that can generate benefits in multiple dimensions, while eliminating negative externalities. The scientific literature sometimes muddies the debate by failing to distinguish between the different objectives implied by concepts of agricultural production versus food production versus food security [35,39]. Political commitment at the highest level is needed to achieve the multiple and interlinked goals of food security, nutrition, poverty reduction, and local development [48].

Outstanding Questions

Can alternative approaches to conventional intensification reduce the environmental harm from agriculture while delivering improved social and economic outcomes? Is there support for the skeptical view that alternative farming systems reduce farmer incomes or have other negative effects? How can farming systems simultaneously foster sustainable agriculture, nutrition, and livelihoods? What solutions are most likely to work in which situations?

How can the results of such assessments be applied by farming communities? How can ecosystem services and other externalities of farming systems be effectively incorporated into decision making? To what degree can decision making for greater sustainability be enhanced by providing scientific evidence to farmers and policy-makers?

Is it possible to conduct a successful participatory approach to improving agriculture when farming communities of many countries are so populous and diverse?

To what degree can ecosystem services replace, complement, or interact synergistically with agricultural inputs to achieve resilient and productive farms?

Under what circumstances does biodiversity improve crop yield?

What is the relative importance of food production, availability, access, and utilization for food security?

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