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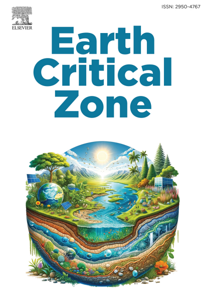


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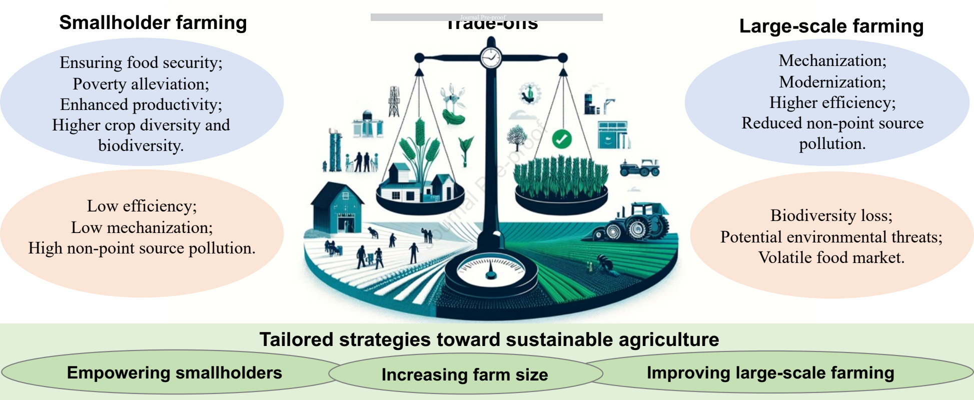
Smallholder farming
Trade-offs
Large-scale farming
Ensuring food security;
Poverty alleviation;
Enhanced productivity;
Higher crop diversity and
biodiversity.
Mechanization;
Modernization;
Higher efficiency;
Reduced non-point source
pollution.
Low efficiency;
Low mechanization;
High non-point source pollution.
Biodiversity loss;
Potential environmental threats;
Volatile food market.
Tailored strategies toward sustainable agriculture
Empowering smallholders
Increasing farm size
Improving large-scale farming

# Trade-offs in Agricultural Outcomes Across Various Farm Sizes

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**Abstract**
Farm size plays a critical role in agriculture, influencing productivity, resource use efficiency, and environmental impacts. Smallholder farms, compared to large farms, often face constraints such as limited mechanization and advanced technology, leading to lower efficiency and potential environmental degradation. Transitioning from a system dominated by smallholders to one featuring large-scale farming holds potential for sustainable agricultural intensification, especially in regions currently reliant on smallholder systems. However, the benefits and potential unintended consequences of such a transition remain contentious and require further exploration. This review examines the multifaceted role of farm size, highlighting the essential contributions of smallholders to food security, poverty alleviation, crop diversity, and biodiversity despite their limitations in machinery, technology and effeciency. While acknowledging the potential for increased sustainability through scaling up farm size, we also indentify the risks associated with large-scale farming, such as biodiversity loss, increased market volatility, and adverse environmental impacts. We emphasize the importance of tailored strategies for managing different farm size to optimize agricultural productivity, economic viability, human well-being, and sustainable development. Our study provides a new perspective that complements the conventional advocacy for large-scale agriculture, revealing trade-offs of agricultural outcomes across different farm sizes. It offers a comprehensive evaluation of the significance of farm size in shaping future sustainable agricultural systems.

**Keywords**: Farm size; Smallholder farming; Sustainable agriculture; Agricultural productivity; Environmental impact; Food security

## 1. Introduction

Agriculture is an indispensable pillar of modern society, providing sustenance and nutrition however it also affects the land use system, freshwater use and climate change (Campbell et al., 2017). Specifically, agriculture contributes substantially to global annual greenhouse gas (GHG) emissions—at 7.1 Gt $CO_2$ equivalent in 2020, which represents 12% of total global annual GHG emissions (Rosa and Gabrielli, 2023). These emissions are largely composed of methane (54%), nitrous oxide (28%), and carbon dioxide (18%) from synthetic fertilizers production and application, manure management and application, and on-farm energy use (Rosa and Gabrielli, 2023). Agriculture is the primary source of eutrophication in regions such as China, caused by nitrogen and phosphorus leaching from fertilizers and manure (Huang et al., 2017). Consequently, sustainable agriculture is pivotal in achieving the Sustainable Development Goals (SDGs), especially in relation to eliminating poverty (SDG1), hunger (SDG2), and in taking climate action (SDG13), as well as in conserving aquatic life (SDG14) and terrestrial ecosystems (SDG15) (FAO and Food and Agriculture Organization of United Nations, 2018; Shahmohamadloo et al., 2022), while at the same time sustaining food demands of a growing global population (Beltran-Peña et al., 2020).The increasing pressures from global warming (IPCC, 2022) underscore the urgent need for sustainable agricultural enhancement and pollution mitigation. Effective strategies investigated include shifting diets (Foley et al., 2011), curbing food waste (Gu et al., 2019), optimizing fertilization application through the 4R principles (right time, right place, right amount, and right composition) (Nkebiwe et al., 2016), integrating livestock and crop systems for optimized manure management (Jin et al., 2021; Marconi and Rosa, 2024), and increasing farm sizes to reduce chemical overuse (Ren et al., 2019). Of these, farm size expansion has been posited as a compelling solution to reduce environmental pollution while maintaining food supply (Duan et al., 2021; Ren et al., 2023a, 2023b; Wu et al., 2018), although its applicability varies across countries and regions.

Farm size is a key determinant for agricultural productivity, environmental impacts, and resource use efficiency (Ren et al., 2019). Typically, farm size is defined by the total area of cropland managed by a farm, which includes both owned and leased land, excluding any land leased out (James M. MacDonald, 2013). Farm size can be measured in terms of cropland area, harvest area, or the value of goods produced or sold (James M. MacDonald, 2013), though the specific definitions can vary depending on the focus of each study (Box 1). Smallholder farms, typically defined as managing less than two hectares of land, often use excessive amounts of fertilizer and agro-chemicals while relying less on mechanization and technology adoption (Gao et al., 2021; Hu et al., 2022; Ren et al., 2021; Ruzzante et al., 2021). Transitioning from small to large average farm sizes is typically accompanied by a shift from variable inputs like fertilizers and pesticides to fixed inputs such as machinery, irrigation, and the promotion to adopt advanced technologies, such as precision farming (Ren et al., 2021). This transition has potential to mitigate non-point source pollution and GHG emissions by reducing chemical fertilizer overuse (Wang et al., 2022; Wu et al., 2018). Empirical evidence supporting the positive effects such a shift can be found across many regions, and most prominently in those dominated by smallholder farms, in countries such as China (Gao et al., 2021; Ju et al., 2016), Slovenia (Bojnec and Latruffe, 2013; Unay Gailhard and Bojnec, 2015), and Nepal (Koirala et al., 2022). These findings highlight the limitations of smallholder farming and the benefits of large-scale farming, suggesting that transitioning away from smallholder farming practices in favor of large-scale agriculture could be a compelling solution for sustainable agriculture intensification due to economy of scale. However, it is important to recognize the multifaceted roles played by both smallholders and large-scale farming. For example, small-scale farms play a crucial role in food security and poverty alleviation, particularly in sub-Saharan Africa

(Collier and Dercon, 2014; Frelat et al., 2016). Additionally, smallholder farming promotes crop diversity, in contrast to larger farms tending towards monocultures, which is linked to higher yields and diverse diet nutrients (Müller et al., 2021; Ricciardi et al., 2021). Conversely, expanding farm sizes often result in substantial losses of both crop species and biodiversity at the field and landscape scales due to monoculture plantations (Herrero et al., 2017; Ricciardi et al., 2021), as well as increased fossil fuel-based energy usage increasing GHG emissions (Rosa et al., 2021). Therefore, it is essential to undertake comprehensive, integrated assessments into effective and suitable ways to manage farming sizes for specific regions and environmental conditions.

This study aims to fill a gap in our understanding by thoroughly exploring the contributions and risks associated with different farm sizes, providing a comprehensive review of the benefits, challenges and their trade-offs across different farm scales. In this study, we consider farm size as the area of cropland operated by the farm, including owned and rented land minus any land rented to others (James M. MacDonald, 2013), focusing exclusively on crop cultivation and excluding livestock and aquaculture. Farm size categories lack a universally accepted definition (Rapsomanikis, 2015). This paper examines three scales: smallholder, medium-scale, and large-scale farms (Fig. 1). Smallholders are typically characterized as farms with less than two hectares of land, though this threshold may vary with studies and regional contexts (Table 1). In contrast, large-scale farms, which may extend over several hundred hectares, are efficient and modernized but associated with potential risks on sustainability. Medium-scale farms are identified as farms ranging in size between smallholder and large-scale operation, balancing the benefits and risks of smallholder and large-scale farming.

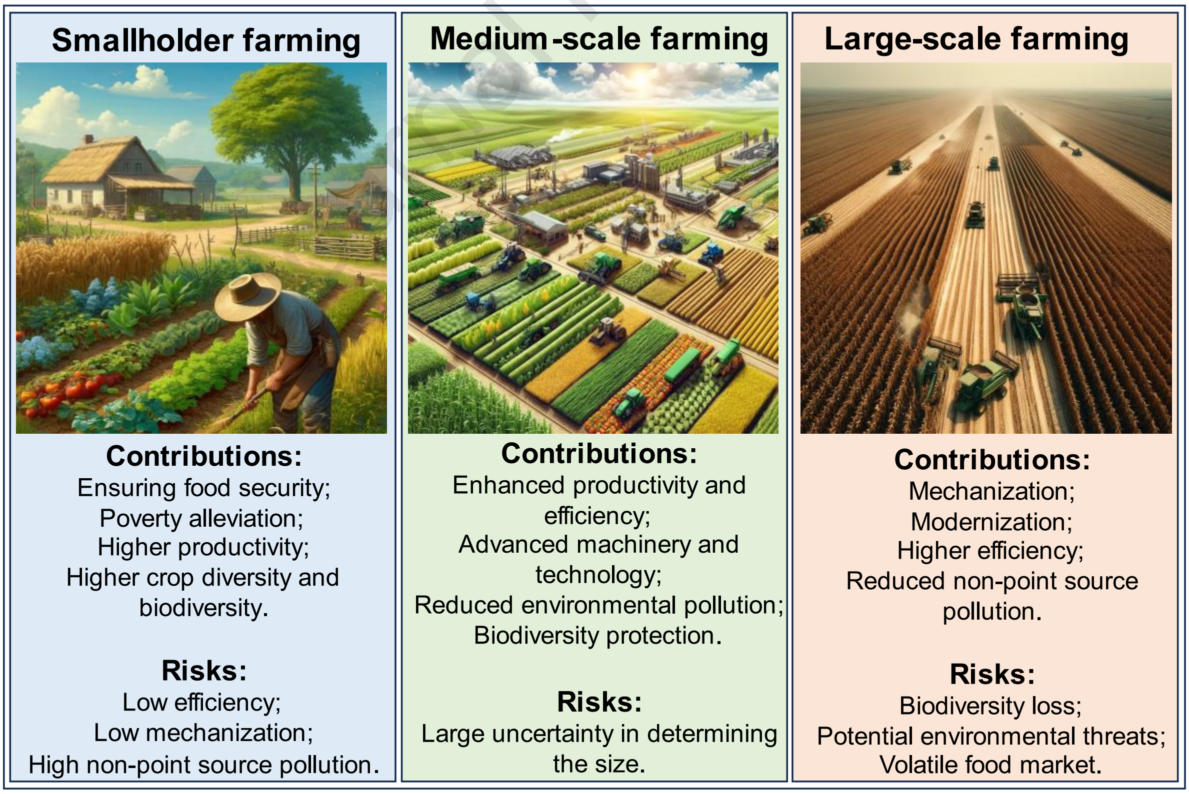


**Fig. 1. Comparisons of contributions and risks across different farm sizes.** This figure summarizes the contributions and risks of smallholder, medium-scale and large-scale farming, which are detailed in the following sections. Smallholder farming contributes to ensuring food

security, poverty alleviation, achieving higher productivity and enhancing crop diversity and biodiversity, while not being suitable for mechanization, reducing efficiency and increasing non-point source pollution. Non-point pollution mainly refers to pollution caused by excess fertilizers, herbicides, and insecticides from agricultural lands and residential areas (U.S. Environmental Protection Agency, 2023). Large-scale farming enables a higher degree of mechanization, modernization, higher efficiency and reduced non-point source pollution, but is subject to risks with crop diversity and biodiversity loss, potential environmental threats and increased vulnerability to volatile food markets. Medium-scale farms can balance benefits and risks of smallholder and large-scale farming, enhancing productivity and efficiency by adopting advanced technology and machinery, yet defining them varies regionally and over time.

**Table 1. Farm size (hectares - ha) in Sub-Saharan Africa and Southeast Asia.** Year indicates the data for that year. Data used in this table is from the Food and Agriculture Organization of the United Nations (FAOSTAT, 2017).

| Region | Country | Year | Smallholder farms (ha) | National average (ha) | Threshold of Smallholder farms (ha) |
|---|---|---|---|---|---|
| Sub-Saharan Africa | Ghana | 2013 | 1.56 | 2.56 | 3.64 |
| | Kenya | 2005 | 0.53 | 0.86 | 1.21 |
| | Ethiopia | 2012 | 0.78 | 1.4 | 1.95 |
| | Malawi | 2011 | 0.47 | 0.71 | 0.91 |
| | Niger | 2011 | 2.91 | 4.57 | 6.60 |
| | Nigeria | 2013 | 0.53 | 0.85 | 1.74 |
| | United Republic of Tanzania | 2013 | 1.20 | 1.89 | 3.31 |
| | Uganda | 2012 | 0.97 | 1.51 | 2.76 |
| Southeast Asia | Bangladesh | 2005 | 0.3 | 0.54 | 0.9 |
| | Nepal | 2003 | 0.46 | 0.7 | 1.02 |
| | Vietnam | 2008 | 0.38 | 0.63 | 1.41 |
| | Cambodia | 2004 | 0.86 | 1.31 | 2.00 |
| | Indonesia | 2000 | 0.56 | 0.92 | 2.00 |

## 2. Methods

To thoroughly assess the impact of farm size on agriculture, we conducted a comprehensive review following a structured approach. Initially, we identified relevant keywords based on the introductory sections and previous studies, including "farm size", "field size", "large-scale farming", "farm scale", "land fragmentation", "smallholders" and "small farms". We searched for literature using these keywords in titles, abstracts, and keywords, focusing on articles, articles in press, and reviews in subject areas related to farm size. Our search encompassed databases such as ScienceDirect, Engineering Village, ISI Web of Science, and Google Scholar, and included major publishers like Elsevier, IEEE Xplore, Springer, and Wiley to ensure a comprehensive coverage of relevant literature.

After reviewering these papers, we focused on those that clearly explained the relationship between farm size and agricultural indicators, while also considering the limitations of each study. The research centered on crop farming, excluding livestock farming, with priority given to studies proposing feasible solutions to existing problems. The summary of cited literature in this review is presented in Table 2, highlighting the geographic distribution of different farm sizes. Smallholders dominated regions like Africa, Southeast Asia, and China, and large-scale farming prevalent areas like the U.S. are all incorporated. Additionally, studies on smallholder farming, farm size expansion, and all farm size types include global-scale analyses. This demonstrates the unbiased and representative nature of our paper selection.

The structure of this paper is as follows: (1) We review the contributions of smallholders to food security, poverty alleviation, productivity, and biodiversity; (2) We discuss the limitations of smallholder farming and the benefits of expanding farm size, including agricultural pollution reduction, climate change adaptation, and social implications for sustainable agriculture; (3) We examine the risks associated with large-scale farming, such as biodiversity loss, potential environmental risks, and volatile food markets; (4) Finally, we provide conclusions, implications and an outlook, summarizing current research on farm size and suggesting directions for future studies.

| **Box 1. Concepts and definitions related farm size.** |
|---|
| **Farm size**: Farm size refers to the area of cropland operated by the farm, including owned and rented land minus any land rented to others (James M. MacDonald, 2013). It may consist of multiple parcels with varying soil quality, topography, and other conditions (Ren et al., 2023b). Measurements can include cropland area, harvest area, and the value of produced or sold goods (James M. MacDonald, 2013). Definitions vary based on the specific focus of each study. |
| **Field size**: A field is an enclosed cropland area that includes both annual and perennial crops (Clough et al., 2020; Lesiv et al., 2019). Field size is measured as the continuous area enclosed, distinct from the overall operation of the farm. Field size typically correlates closely with farm size (Clough et al., 2020). |
| **Smallholder farming**: Smallholder farms, while their definition varies, typically refer to farms operated by rural farmers with an area of less than two hectares (Collier and Dercon, 2014; Fan and Chan-Kang, 2005; Ricciardi et al., 2021). |
| **Large-scale farming**: There is no specific boundary to define large-scale farming, as it varies across regions and study objectives. Thresholds for large-scale farming range widely, from 135 hectares in Sweden (Marcacci et al., 2020), 405 hectares in the U.S. (Liebert et al., 2022), to 15 hectares in India (Fan and Chan-Kang, 2005). In this paper, we define large-scale farming as operations exceeding hundreds of hectares with high machinery and technology inputs but having substantial detrimental effects such as biodiversity loss. |
| **Medium-scale farming**: Medium-scale farms ranges in size between smallholder and large-scale operations, and changes dramatically with regions and over time. They are defined as those can balance the benefits and risks across smallholder and large-scale farming, including enhanced farm productivity and efficiency, and advanced machinery and technology, while minimizing environmental impact such as water and air pollution, and biodiversity loss. |

**Table 2. Summary of cited literature related to farm sizeid**

| Farm size category | Study Region | References |
|---|---|---|
| Smallholder farming | Africa | (Burke and Lobell, 2017; Collier and Dercon, 2014; Frelat et al., 2016; Jayne et al., 2014; Koirala et al., 2022; Meemken and Bellemare, 2020; Merlos and Hijmans, 2020; Noack and Larsen, 2019; Omotilewa et al., 2021; Paul and wa Gĩthĩnji, 2018; Sibhatu et al., 2015; Tittonell and Giller, 2013; Unay Gailhard and Bojnec, 2015) |
| | East and Southeast Asia | (Fan and Chan-Kang, 2005; Rigg et al., 2016) |
| | China | (Collier and Dercon, 2014; Cui et al., 2018; Ji et al., 2016; Jin et al., 2021; Li et al., 2013; Ren et al., 2023b, 2021; Tan et al., 2013, 2006; Wang et al., 2018; Wu et al., 2018; Zhang et al., 2019, 2016) |
| | Europe | (Hass et al., 2018) |
| | Global | (Cohn et al., 2017; Lowder et al., 2016; Ricciardi et al., 2021, 2018; Samberg et al., 2016) |
| Farm size expansion | U.S. | (Ao et al., 2021; Key, 2019; Key and Roberts, 2007; Sirami et al., 2019) |
| | China | (Cheng et al., 2022; Duan et al., 2021; Gao et al., 2021; Ju et al., 2016; Wang et al., 2022, 2021) |
| | Europe | (Clough et al., 2020; Noack et al., 2022; Sirami et al., 2019) |
| | Africa | (Jayne et al., 2022, 2016) |
| | Global | (Giua et al., 2022) |
| Large-scale farming | U.S. | (Cai, 2019; Hanson et al., 2008; Haque, 2022; Harrison and Getz, 2015; James M. MacDonald, 2013; Lacy et al., 2023; Liebert et al., 2022; Meehan et al., 2011; Miljkovic, 2005; Prokopy et al., 2019; Ren et al., 2023a; Skaggs and Samani, 2005; Sumner, 2014) |
| | South America | (Graesser et al., 2018) |
| All sizes | Europe | (Belfrage et al., 2015; Bojnec and Latruffe, 2013; Concepción et al., 2012) |
| | Other regions | (Kimhi and Tzur-Ilan, 2021; Marcacci et al., 2020) |
| | Global | (Adamopoulos and Restuccia, 2014; Fritz et al., 2015; Giller et al., 2021; Graeub et al., 2016; Harrison and Getz, 2015; Lesiv et al., 2019; Lowder et al., 2021, 2016, 2014; Ren et al., 2019; Rosa et al., 2021; Ruzzante et al., 2021; Samberg et al., 2016; Su et al., 2022) |

## 3. Results and discussion

### 3.1 Contributions of smallholder farming

Globally, the agricultural sector consists of approximately 570 million farms (Lowder et al., 2016). About 83% of these are smallholder farm have average farm size less than two hectares (Lowder et al., 2016). These small farms collectively occupy up to 40% of global agricultural land (Lesiv et al., 2019), mainly distributed in Sub-Saharan Africa, India, and Southeast Asia (Fig. 2a). Smallholder farms mainly occur in low- and lower-medium-income countries, particularly in regions such as Sub-Saharan Africa, Southeast Asia, South Asia, and China (Lowder et al., 2016; Rigg et al., 2016). Despite constraints such as low mechanization, technology, efficiency (Ren et al., 2019), resilience to climate change (Cohn et al., 2017), and low labor income (Ramankutty et al., 2019), smallholder farming substantially contributes to various aspects of human welfare including food security, poverty alleviation, productivity, and biodiversity conservation, particularly in developing countries.

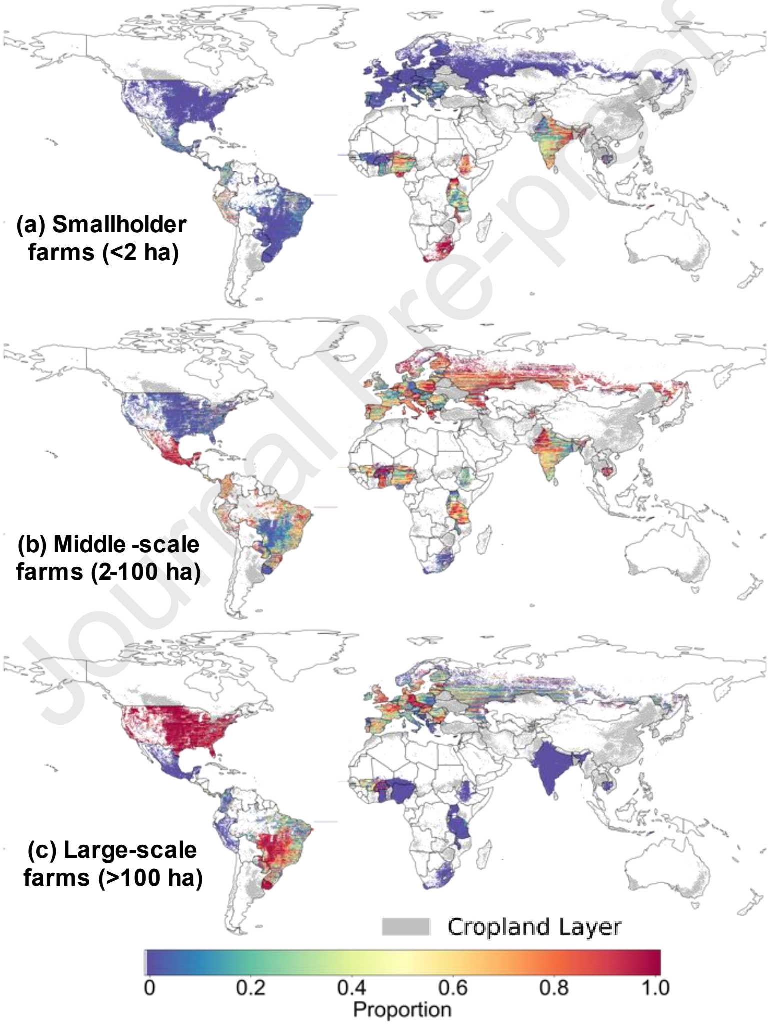


**Fig. 2. Geographic distribution of smallholder, middle-scale and large-scale farming as proportions of total harvest area in 2010.** (a) Share of smallholder farms (< 2 ha); (a) Share of middle-scale farms (2-100 ha); (c) Share of large-scale farms (> 100 ha). Farm size is measured by harvest area in this figure, which are sourced from GAEZv4 crop map (Su et al., 2022). The grey color in this figure indicates cropland distribution (Endalkachew Abebe Kebede et al., 2024) without farm size data.

*Food security.* The critical role of smallholder farms in local and global food security is increasingly recognized (Fan and Chan-Kang, 2005). Prior studies indicate that approximately 30–35% of the total food production are from smallholders, playing a crucial role in ensuring local and global food security (Lowder et al., 2021; Ricciardi et al., 2018). Furthermore, smallholder farms are responsible for 41% of the total global calorie production and 53% of the calories consumed by humans (Samberg et al., 2016). In Sub-Saharan Africa and Southeast Asia, smallholder farms contribute 70-90% of agricultural production (Fig. 3a), with 50-95% of this output being self-sufficient due to limited market access in these regions, thereby enhancing local food security and alleviating hunger (Fig. 3b). In China, smallholder farms produce more than half of all food commodities, particularly fruits (64%), vegetables (60%), sugar crops (59%), roots and tubers (72%), and livestock (63%) (Herrero et al., 2017).

<u>*Poverty alleviation.*</u> Smallholder farms play a critical role in alleviating poverty, supporting millions by providing livelihoods and strengthening local economies (Collier and Dercon, 2014; Rigg et al., 2016). In Sub-Saharan Africa and Southeast Asia, over 70% of the rural population relies on small-scale agriculture for sustenance and income, enhancing both family and community well-being (Fig. 3d). These farms are not only vital sources of food but also generate rural household income, with 60-80% of smallholders' earnings coming from their own agricultural activities (Fig. 3c). Although income from smallholder farming is relatively low and poverty rates remain high in these regions, such efforts are crucial for broader poverty alleviation initiatives. Smallholder farms facilitate direct interactions between farmers and consumers via markets, farm stands, and community-supported agriculture initiatives as well, reinforcing the importance of small-scale farming in local economy (Timmons and Wang, 2010).

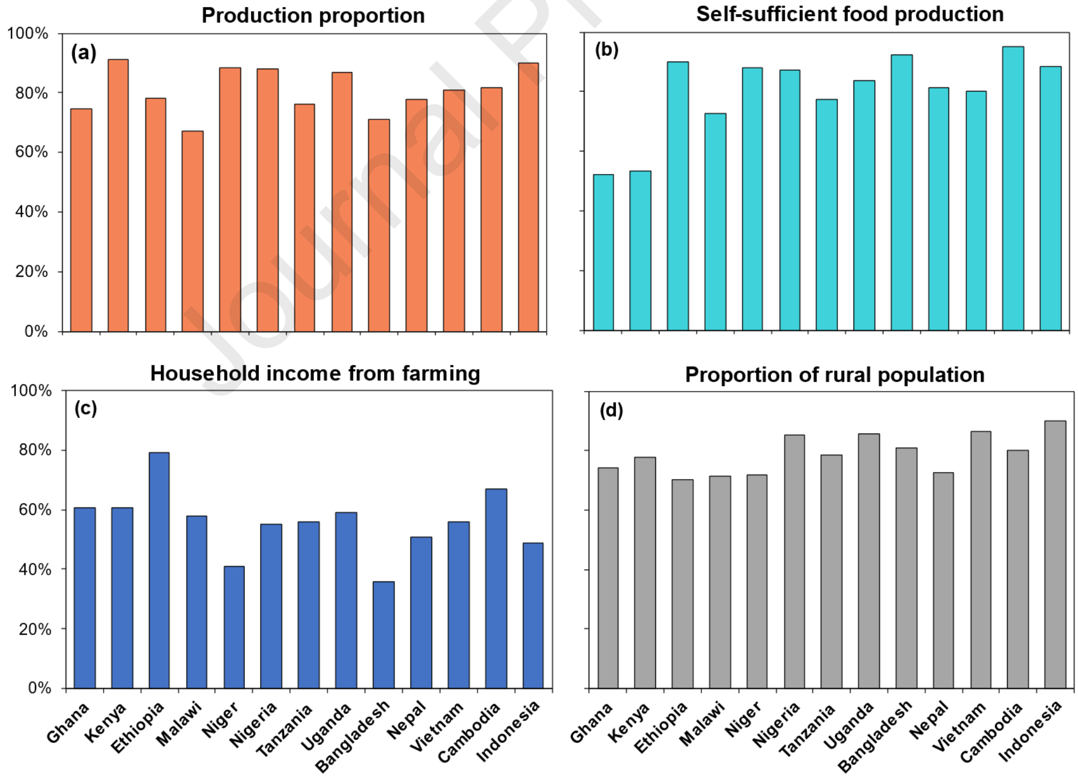


**Fig. 3. Overview of smallholder farming in Sub-Saharan Africa and Southeast Asia**. (a) Production share from smallholder farms; (b) Self-sufficiency in smallholder production; (c) Share of rural household income derived from smallholder farming; (d) Proportion of rural population employed in smallholder farming. Farm size data are listed in Table 1. Data used in this figure is from the Food and Agriculture Organization of the United Nations (FAOSTAT,

2017).

*Enhanced productivity.* Comparative studies reveal that smaller farms frequently achieve higher yields - (both in terms of weight per hectare and value per hectare - compared to larger ones) (Paul and wa Gĩthĩnji, 2018). Specifically, yields typically decrease by 5% for each hectare increase in farm size, a phenomenon mainly attributed to the more intensive and careful management by smallholders who rely heavily on family labor (Ricciardi et al., 2021; Rigg et al., 2016). Despite many smallholders in regions like China being elderly and lacking advanced field management experience, smallholder farms still achieve slightly higher yields (Ren et al., 2023b; Wu et al., 2018). The effectiveness of smallholder farming was notably evident in China during the 1980s, a period of relatively low economic levels and many rural labors, when smallholders substantially contributed to agricultural productivity, accounting for half of the production growth between 1978 and 1984 (Lin, 1991). Furthermore, the practices of smallholder farming in the 1980s in China, which often combined crop planting with livestock raising, typically used less synthetic fertilizer and more manure per cropland area, boosting both crop production and contributing to resource use efficiency and environmental protection (Jin et al., 2021). Productivity is also influenced by factors such as soil quality, available technology, and productive assets like irrigation (Adamopoulos and Restuccia, 2014; Li et al., 2013). This suggests that the relationship between farm size and productivity may vary across regions due to differences in technology and other conditions such as policy context (Ren et al., 2019).

*Crop diversity and biodiversity.* In addition to yields, smaller farms tend to support crop diversity and biodiversity at both the farm and landscape levels, thus enriching ecosystem diversity (Ricciardi et al., 2021). Smaller farms not only enhance crop diversity but also allow farmers the flexibility to tailor their production to meet their dietary needs (Herrero et al., 2017; Sibhatu et al., 2015). This practice is especially crucial in regions burdened by poverty, where diversified cropping systems are vital for providing diverse essential nutrients (Herrero et al., 2017). For biodiversity, small farm sizes enhance biodiversity by increasing field edges (Ricciardi et al., 2021). This structural complexity yields several ecological benefits. For example, it enlarges breeding habitats for arthropods (Ahrenfeldt et al., 2015), offers refuge for small species fleeing disturbed areas (Concepción et al., 2012), increases pollinators and beneficial predators (Ahrenfeldt et al., 2015; Hass et al., 2018), and serves as conservation corridors for arthropods and small mammals (Horgan, 2009). Additionally, the landscape composition of areas dominated by small farms often includes a diverse mix of land cover types, such as forests, wetlands, and fields with different crops or those at various phenological stages, further supporting ecological diversity and sustainability (Lovell et al., 2010; Pekin, 2016).

The evidence above underscores the vital contributions of smallholder farming to global food security and poverty alleviation, while also fostering crop diversity and biodiversity. In regions such as Southeast Asia and Sub-Saharan Africa, where poverty is predominantly in rural areas, a certain number of the rural farmers depend on small-scale farming for their sustenance. While there are limitations in this model, the substantial impact and importance of smallholder farming should not be underestimated.

### 3.2 The importance of increasing farm size from small to medium scale

Smallholder farming faces constraints like limited machinery, technology, and lower efficiency and income (Collier and Dercon, 2014; Fan and Chan-Kang, 2005; Mehrabi et al., 2020). Farm size increases from small to medium scale could address these issues, enhancing efficiency and income. Increasing farm size is a crucial trend, providing substantial benefits to rural farmers

(Jayne et al., 2022), often underappreciated.

*Agricultural pollution reduction.* Increasing farm size to a medium scale has been proven effective in reducing agricultural non-point source pollution related sourced from chemical fertilizers and manure (Wu et al., 2018), which is critical given that it dominates global river pollution (Beusen et al., 2022). As evidenced in China, as farm sizes grew, the application of fertilizers and pesticides per unit area substantially declined (Ju et al., 2016; Wu et al., 2018), mitigating related water and air pollutions. Ammonia emissions were observed to decrease by 0.07% for each 1% increase in average farm size, aiding in the reduction of GHG emissions (Wang et al., 2022). Farm size increases alter the composition of agricultural inputs, enhancing the proportion of fixed inputs like machinery, knowledge, and technology due to economies of scale, which lower the average cost of these inputs (Collier and Dercon, 2014). In contrast, the smallholder farms' low ratio of fixed to total inputs frequently results in over-fertilization as farmers strive to achieve yield targets with inadequate fixed inputs (Ren et al., 2021). Furthermore, farm size increases tend to favor organic over chemical fertilizers, enhancing manure recycling and the use of organic fertilizers, thus reducing agricultural non-point source pollution (Wang et al., 2018). Such farms are also better positioned to adopt environmentally friendly practices (Unay Gailhard and Bojnec, 2015). Globally, farm size increases and cropland nitrogen loss are negatively correlated (Ren et al., 2022), enhancing nitrogen use efficiency and reducing pollution. Increasing farm sizes could potentially decrease global cropland nitrogen loss by 23% by 2100, even with the escalating threats of climate change (Ren et al., 2023a).

*Climate change adaptation*. Previous studies found that there are different impacts and consequences for different farm sizes under climate change (Ren et al., 2023a). For example, cropland nitrogen use efficiency variations related to climate change tend to be much smaller for large and middle-sized farms compared with small ones (Ren et al., 2023a). That is mainly because middle and large farms are usually equipped with better infrastructure, such as machinery and irrigation facilities, which can increase nitrogen use efficiency while maintaining or increasing crop yields under climate change (Ren et al., 2019). Improvements in irrigation practices, including shorter irrigation seasons and more efficient water use (Skaggs and Samani, 2005), help meet crop water needs and addressing heat stress exacerbated by climate change (Rosa et al., 2020). Moreover, farm size influences farmers' willingness to adopt new technologies, the preference for technical solutions, and the methods for gaining agricultural knowledge (Ren et al., 2023b). Larger farms are more likely to adopt new technologies and invest in agricultural education, enhancing their ability to adapt to climate change and minimize negative impacts (Giua et al., 2022; Prokopy et al., 2019; Ruzzante et al., 2021).

*Social implications for sustainable agriculture.* Increasing farm size has profound social implications by streamlining operations, reducing the number of farmers, thus lowering transaction costs, and facilitating the adoption of new technologies and policies (Ren et al., 2022). For example, the medium and large-scale farming and the limited number of farmers in Australia promotes sustainable irrigation practices, reducing potential detrimental impacts on environmental flows and groundwater stocks (Borsato et al., 2020). Transitioning from smallholder to a medium scale can effectively integrate livestock with cropland systems, overcoming the barriers posed by the high transaction costs of numerous smallholder farmers (Zhang et al., 2019). Such a shift also enables a strategic reconfiguration of global crop distribution across existing rainfed and irrigated lands, cutting the consumption of rainwater and irrigation water by 14% and 12%, respectively, without compromising crop diversity, requiring additional cropland, or affecting nutrient and feed availability (Davis et al., 2017). Additionally, medium and large farms typically offer superior job quality compared to smaller ones, providing benefits like higher hourly wages, health insurance, and retirement plans (Harrison and Getz, 2015b). Farmers would benefit directly from farm size increases with higher incomes as well, which is attributed to increased total production and reduced labor inputs (Ren et al., 2021; Tan et al., 2013). In China, consolidating 86% of croplands into a regime of a medium scale with an average field size greater than 16 hectares would lead to a 59% increase in knowledge investments, a 91% increase in machinery use, a 24% reduction in total cropland nitrogen input, an 18% increase in nitrogen use efficiency, and a 39% reduction in labor requirements, while simultaneously doubling labor income (Duan et al., 2021).

Recent decades have witnessed a trend towards increasing farm size globally (Graeub et al., 2016; Ji et al., 2016; Lacy et al., 2023; Lowder et al., 2016). Although it is commonly believed that African agriculture primarily consists of small-scale farms, recent data indicates a rapid growth in medium-scale farms, ranging from 5 to 100 hectares (Jayne et al., 2016). The evolution of farm size is closely linked to economic advancement (Lowder et al., 2016). As countries develop economically, advancements in mechanization, technology, and agronomic practices enhance agricultural productivity (Rapsomanikis, 2015), empowering farm size expansion. In contrast, in low-income regions with limited access to fertilizers, machinery, and technology, smallholder farming remains the best choice. Increasing farm size hinges on improvements in mechanization, technology, and agronomy, addressing smallholders' limitations. For instance, in the U.S. from 1982 to 2012, economic growth and technological advancements coincided with substantial increases in farm size and total factor productivity (Key, 2019; Sumner, 2014). Conversely, mismatches between small farm size and advanced economies and technologies can decrease efficiency and heighten environmental pollution. For example, the discrepancy of small farm size (Ji et al., 2016) and economic advancement (Tan et al., 2013) in China lead to substantial non-point source pollution through the overuse of chemical fertilizers and pesticides (Gao et al., 2021). Empowering smallholders with improved farming practices in China has proven to boost productivity and reduce agricultural pollution but implementing this approach for over 200 million rural households would require substantial resources (Cui et al., 2018; Zhang et al., 2016). These insights underscore the urgency of aligning farm size increases with economic and technological capabilities, especially where smallholders predominate alongside advanced economies and technologies.

### 3.3 Risks of large-scale farming

Increasing farm size can indeed enhance management by incorporating more machinery and advanced knowledge. However, it may also pose risks to biodiversity and food market stability. Between 1940 and 1990, the average U.S. farm size more than doubled, while the number of farms decreased by 67% (Hanson et al., 2008). Large family farms with sales exceeding $250,000 and nonfamily farms (e.g., industrial farms and corporations), which represent only 10% of all farms, now account for 72% of the value of agricultural production in the U.S. (Hanson et al., 2008). Global large-scale farms with harvest area over 100 hectares are predominantly found in the U.S. and South America (Fig. 2b). Although large farms and corporations have substantially contributed to the growth in agricultural modernization, and efficiency, the potential risks associated with large-scale farming should not be overlooked.

<u>*Biodiversity loss.*</u> Biodiversity loss is notably higher on large farms compared to smaller ones, due to substantially lower on-farm landscape heterogeneity (Belfrage et al., 2015). Studies have shown strong positive correlations between on-farm landscape heterogeneity and the number

of breeding birds, butterflies, and herbaceous plant species (Belfrage et al., 2015). For instance, the expansion of farm size along the former inner German border led to a 15% reduction in bird diversity (Noack et al., 2022). This biodiversity loss is largely attributed to landscape simplification driven by large-scale monocultures and shortened crop rotations, which are common in Europe and North America as they simplify production techniques and focus on high-demand crops (Tscharntke et al., 2021). In the U.S., agriculture is dominated by a few major annual crops like maize, soybean, and wheat, often cultivated in fields with very low temporal diversity (Merlos and Hijmans, 2020). Diverse crop rotations are increasingly scarce, often limited to single crop sequences or standard sequences involving only up to three crop species such as wheat, barley, and oilseed rape (Bennett et al., 2012; Steinmann and Dobers, 2013). Additionally, large-scale farming alters land use dynamics, leading to deforestation and biodiversity threats (Graesser et al., 2018). As a result, landscape-scale biodiversity loss is observable in relation to large-scale farming practices.

*Potential environmental threats.* Agricultural environmental impacts are directly linked to farm size, with increasing farm size from smallholder farming helping to reduce agricultural pollution (Ren et al., 2021). However, environmental outcomes might exhibit a U-shaped relationship with a continued increase in farm size, suggesting that larger sizes are not necessarily better from an ecological perspective (Cheng et al., 2022). Transitioning to large-scale commercial farming from medium-sized farms typically requires higher inputs of fertilizers, pesticides, machinery, and mechanized irrigation systems, potentially increasing energy use and carbon emissions (Rosa et al., 2021). A national survey of 542 organic fruit and vegetable farmers in the U.S. revealed that larger farms (≥405 cropland hectares) employed fewer agroecological practices compared to smaller farms (Liebert et al., 2022). Furthermore, large farm sizes could lead to increased groundwater use and depletion as farms adopt more intensive irrigation technologies, such as switching from traditional center pivot to drop nozzle center pivot systems, which increase water use (Ao et al., 2021). Additionally, simplified crop cultivation and rotations in large-scale farming deplete soil fertility, exacerbate pest infestations and resistance through repeated pesticide applications (Schellhorn et al., 2015), and pose risks of resource bottlenecks for pollinators and biocontrol agents (Tscharntke et al., 2021).

*Volatile food market.* The commercialization of North American farms has intensified in recent years, marked by a decrease in the number of farms and an increase in farm size (Hanson et al., 2008). This shift has led to the concentration of food production and processing into fewer commercial operations (Hanson et al., 2008), resulting in a less resilient food market vulnerable to price fluctuations and market instability during economic crises or other threats (Levins and Cochrane, 1996; Mark and Kevin, 1987). When a small number of large farms dominate production, environmental variability, crop failure, pest outbreak, or regulatory change on one of these farms can have disproportionate effects on the overall supply chain. As a result, consumers are exposed to a lower and more volatile food supply, which poses substantial risks to food security (Tan et al., 2013). Moreover, as farm sizes increase, there is a concern over the reduced diversity of cultivated species, especially those that are highly nutritious, further threatening food market (Herrero et al., 2017; Müller et al., 2021).

Even though large-scale farming with advanced technology and machinery contribute to higher efficiency and modern agriculture, the risks of large-scale farming on biodiversity, food market stability, and environmental sustainability should be cautious. Addressing these challenges requires a balanced approach that considers the ecological, economic, and social impacts of agriculture to ensure sustainability and resilience in food production systems.

## 4. Managing farming size towards sustainable agriculture

To balance the trade-offs of different farm sizes, tailored measures are essential. Firstly, increasing farm size to a medium scale—determined by local land resources, socioeconomic conditions, and environmental factors (Ren et al., 2019; Tan et al., 2006)—can be effective. This strategy, which has lower transaction costs for agricultural management, is a long-term approach. Secondly, for regions facing challenges that prevent immediate adjustment of farm size, short-term measures should be adopted to address the associated risks. Thus, both long-term and short-term strategies can complement each other to promote agricultural sustainability. In this section, we discuss both strategies to increase farm size and approaches to manage smallholders and large-scale farming to achieve sustainable agriculture (Fig. 4).

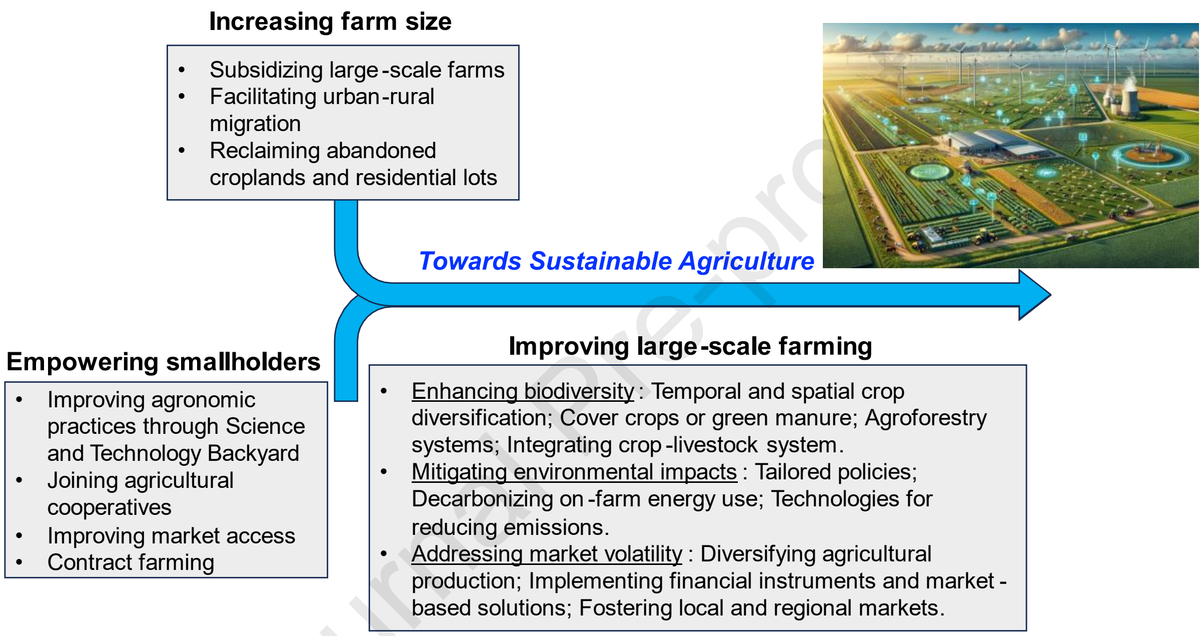


**Fig. 4. Strategies for managing farm size towards sustainable agriculture.** This figure summarizes the strategies by increasing farm size and managing smallholders and large-scale farming to achieve sustainable agriculture. For regions dominated with smallholder farming, increasing farm size is a critical way. For regions with large-scale farming or those unable to adjust farm size soon, managing the current farm size is essential. Science and Technology Backyard is a platform through collaborations between government, researchers, businesses, and smallholders, to advance participatory innovation and technology transfer while securing public and private support (Zhang et al., 2016).

*Increasing farm size*. Farm size changes are influenced by various factors such as land ownership, land resources, and topographical conditions (James M. MacDonald, 2013). For instance, in China, communal ownership of cropland, the large number of rural farmers, and the cropland distribution based on egalitarian principles contribute substantially to smaller farm sizes, making it challenging to scale up (Tan et al., 2006). Conversely, in the U.S., private land ownership and sparsely populated croplands facilitate farm size expansion through free-market land transactions (Ren et al., 2019). Policy changes are crucial for initiating farm size increases despite constraints in land resources and topography. For example, subsidy policies play a crucial role in promoting farm size increase. From 1900 to 2002, the average farm size in the U.S. tripled, driven partly by larger farms receiving substantial subsidies (Cai, 2019; Haque, 2022). Additionally, policies that facilitate urban–rural migration and promote the development of rural nonfarm sectors can decrease the rural population, resulting in a higher per-capita cropland area for rural residents and, consequently, increased farm size (Wang et al., 2021). The croplands of migrating farmers can be consolidated for medium-scale farming, and their rural residential lots can be reclaimed for agricultural use (Gu et al., 2019). Over the past decade, more than 40,000 hectares of lands previously used as residential lots have been reclaimed in China, contributing to an increase in cropland area and supporting the expansion of farm sizes (Wang et al., 2021). Given the ongoing process of urbanization, an increase in farm size is expected globally. However, rapid population growth in some developing regions may compromise this process.

*Empowering smallholders.* The persistence of smallholder farming is anticipated to continue due to several factors, including the economics of small-scale agriculture, relevant farm policies, and the dynamics of smallholder livelihoods within the global economy (Rigg et al., 2016). Transitioning from smallholder farming to mid-size farming in the near future is challenging for some developing countries. Therefore, empowering smallholders with improved agronomic practices for sustainable agriculture is crucial in the short term (Tittonell and Giller, 2013). Innovative methods such as the Science and Technology Backyard (STB) platform have proven effective in China (Zhang et al., 2016). This approach, through collaborations between government, researchers, businesses, and smallholders, advances participatory innovation and technology transfer while securing public and private support. Improved farming methods also contribute to reducing ammonia and carbon dioxide emissions, enhancing air quality and farm profitability (Cui et al., 2018; Kang et al., 2023). Additionally, joining agricultural cooperatives (Cheng et al., 2022), improving market access (Frelat et al., 2016), contract farming (Meemken and Bellemare, 2020), employing high-resolution satellite imagery to predict smallholder productivity (Burke and Lobell, 2017) and adopting digital agriculture (Basso and Antle, 2020) have all benefited the enhancement of smallholder farming practices, enabling swifter transformations in rural livelihoods.

*Improving large-scale farming.* Considering the risks of biodiversity loss, environmental threats, and market fluctuations associated with large-scale farming, it is imperative to adopt specific measures to address these risks and promote sustainable agriculture. Effective strategies to enhance biodiversity include temporal and spatial crop diversification (Gurr et al., 2016; Sirami et al., 2019), using cover crops or manure, implementing agroforestry systems that integrate trees with crops (Niether et al., 2020; Toledo-Hernández et al., 2021), integrating crop-livestock systems (Smith et al., 2020), establishing biodiversity refuges, such as buffer strips and enlarged natural perimeters (Ricciardi et al., 2021), along with other biodiversity-friendly practices (Rosa-Schleich et al., 2019). Creating semi-natural habitats adjacent to croplands, such as hedges and woody or herbaceous patches (Rosa-Schleich et al., 2019), can facilitate biodiversity spillover to smaller fields and enhance on-farm biodiversity (Marcacci et al., 2020; Tscharntke et al., 2021). For environmental impacts, tailored policies are necessary to mitigate the adverse effects of large-scale farming. These include directives like the Nitrates Directive in Europe, which controls nitrate pollution and water quality, and the Habitats Directive of 1992 in Europe, aimed at environmental protection and nature conservation (Giller et al., 2021). Additionally, strategies such as decarbonizing on-farm energy use, sustainably managing nitrogen fertilizers, implementing technologies to reduce enteric methane emissions, and employing carbon dioxide removal technologies are essential for reducing the environmental footprint of large-scale agriculture (Rosa et al., 2021; Rosa and Gabrielli, 2023). To address the volatile food market, it is crucial to diversify agricultural production not only by crop type but also by geographical and operational spread (Paut et al., 2019; Valencia et al., 2019). Encouraging a mix of farm sizes and reducing dependency on a handful of large producers can enhance market stability. Moreover, implementing robust financial instruments and market-based solutions such as futures contracts and insurance can provide farmers with a safety net against price volatility (Fu et al., 2023). Additionally, fostering local and regional markets can reduce the reliance on global supply chains, which are often more vulnerable to fluctuating international market conditions. These strategies collectively can help stabilize markets affected by the centralization of agricultural production in large-scale farming environments.

Expanding farm size could offer a cost-effective solution for regions like China with advanced economies and technology levels (Duan et al., 2021). Nevertheless, for regions encountering challenges that hinder immediate adjustments to farm size, tailored measures are warranted. It is essential to approach farm size increases cautiously, aiming to achieve the medium-scale farming tailored to each region's specific conditions. However, determining this size poses considerable challenges, as it involves various assessment criteria and methodologies. Therefore, a combination of strategies to increase farm size and manage different farm sizes to address associated risks may present a more practical and efficient approach to attaining sustainable agriculture. A typical example is the effectiveness of empowered smallholder farming in South China with its hilly topography (Cui et al., 2018; Zhang et al., 2016) and large-scale farming in Northeast China with its plains (Wang et al., 2022; Zhang et al., 2021). Both approaches enhance crop productivity, reduce pollution, and promote technology adoption, contributing to sustainable agriculture.

## 5. Conclusion, Implications and Outlook

This review illustrates the multifaceted role of farm size in agricultural systems, highlighting potential benefits, risks and trade-offs of changing farm systems at different farm scales. Our findings underscore the critical contributions of smallholders to safeguarding food security and poverty alleviation despite the constraints they are facing, while demonstrating that increasing farm size to medium-scale farming can facilitate modernization and technological advancements, benetifting sustainable agriculture. However, the risks associated with scaling up to large-scale farming, such as biodiversity loss, market fluctuations, and negative environmental impacts, cannot be overlooked. Our analysis indicates that tailored strategies for an effective management of farm sizes are essential to optimize agricultural output while promoting human well-being and sustainable development.

This review thoroughly examines the nuanced impacts of farm size, challenging conventional perspectives that criticize smallholder farming while promoting large-scale operations. It shows the trade-offs in agricultural outcomes across different farm sizes, contributing to a more informed discourse aimed at developing resilient and sustainable agricultural practices capable of meeting global food demands in an environmentally responsible and economically viable manner. This study is significant for policymakers, agricultural practitioners, and researchers aiming to optimize agricultural systems for sustainability. Policymakers should consider the diverse roles of farm size when developing agricultural policies to ensure the sustainability of both the environment and the communities dependent on agriculture for their livelihoods.

Future research should explore the intricate relationship between environmental impacts and farm size, analyzing variables such as fertilizer and pesticide inputs, energy and water consumption, and effects on biodiversity, including soil biodiversity. This investigation should extend to understanding how different farm sizes contribute to achieving net-zero GHG emissions and mitigating climate change. Additionally, broader examination of farm size's role in enhancing agricultural sustainability should encompass socio-economic aspects like poverty alleviation, market stability, policy implementation, and social equity. Future studies should determine optimal farm sizes to maximize sustainability benefits while mitigating risks across diverse contexts. Such research could begin with case studies in regions like China and Sub-Saharan Africa, where sustainable agriculture has not yet been fully implemented. By fostering a holistic understanding of how farm size influences multiple facets of sustainability, future studies can provide actionable insights that guide policymakers, stakeholders, and farming communities in making informed decisions that balance agricultural productivity with ecological and social responsibilities.

**CRediT authorship contribution statement**

Chenchen Ren: Writing – original draft, Visualization, Conceptualization. Liyin He & Yuchi Ma: Conceptualization, Writing – review & editing. Stefan Reis, Hans Van Grinsven, Shu Kee Lam & Lorenzo Rosa: Writing – review & editing.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**References**

Adamopoulos, T., Restuccia, D., 2014. The Size Distribution of Farms and International Productivity Differences. American Economic Review 104, 1667–1697. https://doi.org/10.1257/aer.104.6.1667

Ahrenfeldt, E.J., Klatt, B.K., Arildsen, J., Trandem, N., Andersson, G.K.S., Tscharntke, T., Smith, H.G., Sigsgaard, L., 2015. Pollinator communities in strawberry crops – variation at multiple spatial scales. Bull Entomol Res 105, 497–506. https://doi.org/10.1017/S000748531500036X

Ao, Y.Z., Hendricks, N.P., Marston, L.T., 2021. Growing farms and groundwater depletion in the Kansas High Plains. Environmental Research Letters 16. https://doi.org/10.1088/1748-9326/ac1816

Basso, B., Antle, J., 2020. Digital agriculture to design sustainable agricultural systems. Nat Sustain 3, 254–256. https://doi.org/10.1038/s41893-020-0510-0

Belfrage, K., Björklund, J., Salomonsson, L., 2015. Effects of Farm Size and On-Farm Landscape Heterogeneity on Biodiversity—Case Study of Twelve Farms in a Swedish Landscape. Agroecology and Sustainable Food Systems 39, 170–188. https://doi.org/10.1080/21683565.2014.967437

Beltran-Peña, A., Rosa, L., D'Odorico, P., 2020. Global food self-sufficiency in the 21st century under sustainable intensification of agriculture. Environmental Research Letters 15, 095004. https://doi.org/10.1088/1748-9326/ab9388

Bennett, A.J., Bending, G.D., Chandler, D., Hilton, S., Mills, P., 2012. Meeting the demand for crop production: the challenge of yield decline in crops grown in short rotations. Biological Reviews 87, 52–71. https://doi.org/10.1111/j.1469-185X.2011.00184.x

Beusen, A.H.W., Doelman, J.C., Van Beek, L.P.H., Van Puijenbroek, P.J.T.M., Mogollón, J.M., Van Grinsven, H.J.M., Stehfest, E., Van Vuuren, D.P., Bouwman, A.F., 2022. Exploring river nitrogen and phosphorus loading and export to global coastal waters in the Shared Socio-economic pathways. Global Environmental Change 72, 102426. https://doi.org/10.1016/j.gloenvcha.2021.102426

Bojnec, Š., Latruffe, L., 2013. Farm size, agricultural subsidies and farm performance in Slovenia. Land use policy 32, 207–217. https://doi.org/10.1016/j.landusepol.2012.09.016

Borsato, E., Rosa, L., Marinello, F., Tarolli, P., D'Odorico, P., 2020. Weak and Strong Sustainability of Irrigation: A Framework for Irrigation Practices Under Limited Water Availability. Front Sustain Food Syst 4. https://doi.org/10.3389/fsufs.2020.00017

Burke, M., Lobell, D.B., 2017. Satellite-based assessment of yield variation and its determinants in smallholder African systems. Proc Natl Acad Sci U S A 114, 2189–2194. https://doi.org/10.1073/pnas.1616919114

Cai, W., 2019. Technology, policy distortions, and the rise of large farms. Int Econ Rev (Philadelphia) 60, 387–411. https://doi.org/10.1111/iere.12357

Campbell, B.M., Beare, D.J., Bennett, E.M., Hall-Spencer, J.M., Ingram, J.S.I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J.A., Shindell, D., 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecology and Society 22, art8. https://doi.org/10.5751/ES-09595-220408

Cheng, J., Wang, Q., Zhang, H., Matsubara, T., Yoshikawa, N., Yu, J., 2022. Does Farm Size Expansion Improve the Agricultural Environment? Evidence from Apple Farmers in China. Agriculture (Switzerland) 12. https://doi.org/10.3390/agriculture12111800

Clough, Y., Kirchweger, S., Kantelhardt, J., 2020. Field sizes and the future of farmland biodiversity in European landscapes. Conserv Lett. https://doi.org/10.1111/conl.12752

Cohn, A.S., Newton, P., Gil, J.D.B., Kuhl, L., Samberg, L., Ricciardi, V., Manly, J.R., Northrop, S., 2017. Smallholder Agriculture and Climate Change. Annu Rev Environ Resour 42, 347–

375. https://doi.org/10.1146/annurev-environ-102016-060946

Collier, P., Dercon, S., 2014. African Agriculture in 50 Years: Smallholders in a Rapidly Changing World? World Dev 63, 92–101. https://doi.org/10.1016/j.worlddev.2013.10.001

Concepción, E.D., Fernández-González, F., Díaz, M., 2012. Plant diversity partitioning in Mediterranean croplands: effects of farming intensity, field edge, and landscape context. Ecological Applications 22, 972–981. https://doi.org/10.1890/11-1471.1

Cui, Z., Zhang, H., Chen, X., Zhang, C., Ma, W., Huang, C., Zhang, W., Mi, G., Miao, Y., Li, X., Gao, Q., Yang, J., Wang, Z., Ye, Y., Guo, S., Lu, J., Huang, J., Lv, S., Sun, Y., Liu, Y., Peng, X., Ren, J., Li, S., Deng, X., Shi, X., Zhangc, Q., Yang, Z., Tang, L., Wei, C., Jia, L., Zhang, J., He, M., Tong, Y., Tang, Q., Zhong, X., Liu, Z., Cao, N., Kou, C., Ying, H., Yin, Y., Jiao, X., Zhang, Q., Fan, M., Jiang, R., Zhang, F., Dou, Z., 2018. Pursuing sustainable productivity with millions of smallholder farmers. Nature 555, 363–366. https://doi.org/10.1038/nature25785

Davis, K.F., Rulli, M.C., Seveso, A., D'Odorico, P., 2017. Increased food production and reduced water use through optimized crop distribution. Nat Geosci 10, 919–924. https://doi.org/10.1038/s41561-017-0004-5

Duan, J., Ren, C., Wang, S., Zhang, X., Reis, S., Xu, J., Gu, B., 2021. Consolidation of agricultural land can contribute to agricultural sustainability in China. Nat Food 2, 1014–1022. https://doi.org/10.1038/s43016-021-00415-5

Endalkachew Abebe Kebede, Kevin Ong'are Oluoch, Stefan Siebert, Piyush Mehta, Sarah Hartman, Jonas Jägermeyr, Deepak Ray, Tariq Ali, Kate A. Brauman, Qinyu Deng, Wei Xie, Kyle Frankel Davis, 2024. A global open-source dataset of monthly irrigated and rainfed cropped areas (MIRCA-OS) for the 21st century. https://doi.org/https://doi.org/10.31223/X5H125

Fan, S., Chan-Kang, C., 2005. Is small beautiful? Farm size, productivity, and poverty in Asian agriculture, in: Agricultural Economics. pp. 135–146. https://doi.org/10.1111/j.0169-5150.2004.00019.x

FAO, 2017. Small Family Farms Data Portrait,Food and Agriculture Organization of the United Nations, https://www.fao.org/family-farming/data-sources/dataportrait/farm-size/en/ [WWW Document].

FAO, Food and Agriculture Organization of United Nations, 2018. 20 Interconnected Actions to Guide Decision-makers.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. https://doi.org/10.1038/nature10452

Frelat, R., Lopez-Ridaura, S., Giller, K.E., Herrero, M., Douxchamps, S., Djurfeldt, A.A., Erenstein, O., Henderson, B., Kassie, M., Paul, B.K., Rigolot, C., Ritzema, R.S., Rodriguez, D., Van Asten, P.J.A., Van Wijk, M.T., 2016. Drivers of household food availability in sub-Saharan Africa based on big data from small farms. Proc Natl Acad Sci U S A 113, 458–463. https://doi.org/10.1073/pnas.1518384112

Fritz, S., See, L., Mccallum, I., You, L., Bun, A., Moltchanova, E., Duerauer, M., Albrecht, F., Schill, C., Perger, C., Havlik, P., Mosnier, A., Thornton, P., Wood-Sichra, U., Herrero, M., Becker-Reshef, I., Justice, C., Hansen, M., Gong, P., Abdel Aziz, S., Cipriani, A., Cumani, R., Cecchi, G., Conchedda, G., Ferreira, S., Gomez, A., Haffani, M., Kayitakire, F., Malanding, J., Mueller, R., Newby, T., Nonguierma, A., Olusegun, A., Ortner, S., Rajak, D.R., Rocha, J., Schepaschenko, D., Schepaschenko, M., Terekhov, A., Tiangwa, A., Vancutsem, C., Vintrou, E., Wenbin, W., van der Velde, M., Dunwoody, A., Kraxner, F.,

Obersteiner, M., 2015. Mapping global cropland and field size. Glob Chang Biol 21, 1980–1992. https://doi.org/10.1111/gcb.12838
Fu, J., Shen, R., Huang, C., 2023. How does price insurance alleviate the fluctuation of agricultural product market? A dynamic analysis based on cobweb model. Agricultural Economics (Zemědělská ekonomika) 69, 202–211. https://doi.org/10.17221/107/2023-AGRICECON
Gao, J., Gai, Q., Liu, B., Shi, Q., 2021. Farm size and pesticide use: evidence from agricultural production in China. China Agricultural Economic Review 13, 912–929. https://doi.org/10.1108/CAER-11-2020-0279
Giller, K.E., Delaune, T., Silva, J.V., Descheemaeker, K., van de Ven, G., Schut, A.G.T., van Wijk, M., Hammond, J., Hochman, Z., Taulya, G., Chikowo, R., Narayanan, S., Kishore, A., Bresciani, F., Teixeira, H.M., Andersson, J.A., van Ittersum, M.K., 2021. The future of farming: Who will produce our food? Food Secur 13, 1073–1099. https://doi.org/10.1007/s12571-021-01184-6
Giua, C., Materia, V.C., Camanzi, L., 2022. Smart farming technologies adoption: Which factors play a role in the digital transition? Technol Soc 68. https://doi.org/10.1016/j.techsoc.2022.101869
Graesser, J., Ramankutty, N., Coomes, O.T., 2018. Increasing expansion of large-scale crop production onto deforested land in sub-Andean South America. Environmental Research Letters 13, 084021. https://doi.org/10.1088/1748-9326/aad5bf
Graeub, B.E., Chappell, M.J., Wittman, H., Ledermann, S., Kerr, R.B., Gemmill-Herren, B., 2016. The State of Family Farms in the World. World Dev 87, 1–15. https://doi.org/10.1016/j.worlddev.2015.05.012
Gu, B., Zhang, X., Bai, X., Fu, B., Chen, D., 2019. Four steps to food security for swelling cities. Nature 566, 31–33. https://doi.org/10.1038/d41586-019-00407-3
Gurr, G.M., Lu, Z., Zheng, X., Xu, H., Zhu, P., Chen, G., Yao, X., Cheng, J., Zhu, Z., Catindig, J.L., Villareal, S., Van Chien, H., Cuong, L.Q., Channoo, C., Chengwattana, N., Lan, L.P., Hai, L.H., Chaiwong, J., Nicol, H.I., Perovic, D.J., Wratten, S.D., Heong, K.L., 2016. Multi-country evidence that crop diversification promotes ecological intensification of agriculture. Nat Plants 2, 16014. https://doi.org/10.1038/nplants.2016.14
Hanson, J.D., Hendrickson, J., Archer, D., 2008. Challenges for maintaining sustainable agricultural systems in the United States. Renewable Agriculture and Food Systems 23, 325–334. https://doi.org/10.1017/S1742170507001974
Haque, S., 2022. US federal farm payments and farm size: Quantile estimation on panel data. J Agric Econ 73, 139–154. https://doi.org/10.1111/1477-9552.12437
Harrison, J.L., Getz, C., 2015. Farm size and job quality: mixed-methods studies of hired farm work in California and Wisconsin. Agric Human Values 32, 617–634. https://doi.org/10.1007/s10460-014-9575-6
Hass, A.L., Kormann, U.G., Tscharntke, T., Clough, Y., Baillod, A.B., Sirami, C., Fahrig, L., Martin, J.L., Baudry, J., Bertrand, C., Bosch, J., Brotons, L., Bure, F., Georges, R., Giralt, D., Marcos-García, M., Ricarte, A., Siriwardena, G., Batáry, P., 2018. Landscape configurational heterogeneity by small-scale agriculture, not crop diversity, maintains pollinators and plant reproduction in western Europe. Proceedings of the Royal Society B: Biological Sciences 285. https://doi.org/10.1098/rspb.2017.2242
Herrero, A.M., Thornton, P K, Power, B, Bogard, J R, Waha, K, Stephenson, E, Herrero, M., Thornton, Philip K, Power, Brendan, Bogard, Jessica R, Remans, R., Fritz, S., Gerber, J.S., Nelson, G., See, L., Waha, Katharina, Watson, R.A., West, P.C., Samberg, L.H., van de Steeg, J., Stephenson, Eloise, van Wijk, M., Havlík, P., 2017. Farming and the geography of nutrient production for human use: a transdisciplinary analysis, Articles Lancet Planet

Health.
Horgan, F.G., 2009. Invasion and retreat: shifting assemblages of dung beetles amidst changing agricultural landscapes in central Peru. Biodivers Conserv 18, 3519–3541. https://doi.org/10.1007/s10531-009-9658-7
Hu, Y., Li, B., Zhang, Z., Wang, J., 2022. Farm size and agricultural technology progress: Evidence from China. J Rural Stud 93, 417–429. https://doi.org/10.1016/j.jrurstud.2019.01.009
Huang, J., Xu, C., Ridoutt, B.G., Wang, X., Ren, P., 2017. Nitrogen and phosphorus losses and eutrophication potential associated with fertilizer application to cropland in China. J Clean Prod 159, 171–179. https://doi.org/10.1016/j.jclepro.2017.05.008
IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.
James M. MacDonald, P.K.R.A.H., 2013. Farm Size and the Organization of U.S. Crop Farming. ERR-152. U.S. Department of Agriculture, Economic Research Service.
Jayne, T.S., Chamberlin, J., Headey, D.D., 2014. Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. Food Policy 48, 1–17. https://doi.org/10.1016/j.foodpol.2014.05.014
Jayne, T.S., Chamberlin, J., Traub, L., Sitko, N., Muyanga, M., Yeboah, F.K., Anseeuw, W., Chapoto, A., Wineman, A., Nkonde, C., Kachule, R., 2016. Africa's changing farm size distribution patterns: the rise of medium-scale farms. Agricultural Economics (United Kingdom) 47, 197–214. https://doi.org/10.1111/agec.12308
Jayne, T.S., Wineman, A., Chamberlin, J., Muyanga, M., Yeboah, F.K., 2022. Changing Farm Size Distributions and Agricultural Transformation in Sub-Saharan Africa. Annual Review ofResource Economics 109–30. https://doi.org/10.1146/annurev-resource-111220
Ji, X., Rozelle, S., Huang, J., Zhang, L., Zhang, T., 2016. Are China's Farms Growing? China and World Economy 24, 41–62. https://doi.org/10.1111/cwe.12143
Jin, S., Zhang, B., Wu, B., Han, D., Hu, Y., Ren, C., Zhang, C., Wei, X., Wu, Y., Mol, A.P.J., Reis, S., Gu, B., Chen, J., 2021. Decoupling livestock and crop production at the household level in China. Nat Sustain 4, 48–55. https://doi.org/10.1038/s41893-020-00596-0
Ju, X., Gu, B., Wu, Y., Galloway, J.N., 2016. Reducing China's fertilizer use by increasing farm size. Global Environmental Change 41, 26–32. https://doi.org/10.1016/j.gloenvcha.2016.08.005
Kang, J., Wang, J., Heal, M.R., Goulding, K., de Vries, W., Zhao, Y., Feng, S., Zhang, X., Gu, B., Niu, X., Zhang, H., Liu, X., Cui, Z., Zhang, F., Xu, W., 2023. Ammonia mitigation campaign with smallholder farmers improves air quality while ensuring high cereal production. Nat Food 4, 751–761. https://doi.org/10.1038/s43016-023-00833-7
Key, N., 2019. Farm size and productivity growth in the United States Corn Belt. Food Policy 84, 186–195. https://doi.org/10.1016/j.foodpol.2018.03.017
Key, N.D., Roberts, M.J., 2007. Do Government Payments Influence Farm Size and Survival?, Source: Journal of Agricultural and Resource Economics.
Kimhi, A., Tzur-Ilan, N., 2021. Structural changes in israeli family farms: Long-run trends in the farm size distribution and the role of part-time farming. Agriculture (Switzerland) 11. https://doi.org/10.3390/agriculture11060518
Koirala, P., Kotani, K., Managi, S., 2022. How do farm size and perceptions matter for farmers' adaptation responses to climate change in a developing country? Evidence from Nepal. Econ

Anal Policy 74, 188–204. https://doi.org/10.1016/j.eap.2022.01.014
Lacy, K., Orazem, P.F., Schneekloth, S., 2023. Measuring the American farm size distribution. Am J Agric Econ 105, 219–242. https://doi.org/10.1111/ajae.12318
Lesiv, M., Laso Bayas, J.C., See, L., Duerauer, M., Dahlia, D., Durando, N., Hazarika, R., Kumar Sahariah, P., Vakolyuk, M., Blyshchyk, V., Bilous, A., Perez-Hoyos, A., Gengler, S., Prestele, R., Bilous, S., Akhtar, I. ul H., Singha, K., Choudhury, S.B., Chetri, T., Malek, Ž., Bungnamei, K., Saikia, A., Sahariah, D., Narzary, W., Danylo, O., Sturn, T., Karner, M., McCallum, I., Schepaschenko, D., Moltchanova, E., Fraisl, D., Moorthy, I., Fritz, S., 2019. Estimating the global distribution of field size using crowdsourcing. Glob Chang Biol 25, 174–186. https://doi.org/10.1111/gcb.14492
Levins, R.A., Cochrane, W.W., 1996. The Treadmill Revisited. Land Econ 72, 550. https://doi.org/10.2307/3146915
Li, G., Feng, Z., You, L., Fan, L., 2013. Re-examining the inverse relationship between farm size and efficiency. China Agricultural Economic Review 5, 473–488. https://doi.org/10.1108/CAER-09-2011-0108
Liebert, J., Benner, R., Bezner Kerr, R., Björkman, T., De Master, K.T., Gennet, S., Gómez, M.I., Hart, A.K., Kremen, C., Power, A.G., Ryan, M.R., 2022. Farm size affects the use of agroecological practices on organic farms in the United States. Nat Plants 8, 897–905. https://doi.org/10.1038/s41477-022-01191-1
Lin, J.Y., 1991. The household responsibility system reform and the adoption of hybrid rice in China. J Dev Econ 36, 353–372. https://doi.org/10.1016/0304-3878(91)90041-S
Lovell, S.T., Mendez, V.E., Erickson, D.L., Nathan, C., DeSantis, S., 2010. Extent, pattern, and multifunctionality of treed habitats on farms in Vermont, USA. Agroforestry Systems 80, 153–171. https://doi.org/10.1007/s10457-010-9328-5
Lowder, S.K., Sánchez, M. V., Bertini, R., 2021. Which farms feed the world and has farmland become more concentrated? World Dev 142. https://doi.org/10.1016/j.worlddev.2021.105455
Lowder, S.K., Skoet, J., Raney, T., 2016. The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide. World Dev 87, 16–29. https://doi.org/10.1016/j.worlddev.2015.10.041
Lowder, S.K., Skoet, J., Singh, S., 2014. What do we really know about the number and distribution of farms and family farms worldwide? Background paper for The State of Food and Agriculture 2014, ESA Working Paper No. 14-02.
Marcacci, G., Gremion, J., Mazenauer, J., Sori, T., Kebede, F., Ewnetu, M., Christe, P., Arlettaz, R., Jacot, A., 2020. Large-scale versus small-scale agriculture: Disentangling the relative effects of the farming system and semi-natural habitats on birds' habitat preferences in the Ethiopian highlands. Agric Ecosyst Environ 289, 106737. https://doi.org/10.1016/j.agee.2019.106737
Marconi, P., Rosa, L., 2024. Global potential nitrogen recovery from anaerobic digestion of agricultural residues. Environmental Research Letters 19, 054050. https://doi.org/10.1088/1748-9326/ad428e
Mark, R., Kevin, R., 1987. Crisis By Design: A Brief Review of U.S. Farm Policy. League of Rural Voters Education Project.
Meehan, T.D., Werling, B.P., Landis, D.A., Gratton, C., 2011. Agricultural landscape simplification and insecticide use in the Midwestern United States. Proc Natl Acad Sci U S A 108, 11500–11505. https://doi.org/10.1073/pnas.1100751108
Meemken, E.-M., Bellemare, M.F., 2020. Smallholder farmers and contract farming in developing countries. Proceedings of the National Academy of Sciences 117, 259–264. https://doi.org/10.1073/pnas.1909501116

Mehrabi, Z., McDowell, M.J., Ricciardi, V., Levers, C., Martinez, J.D., Mehrabi, N., Wittman, H., Ramankutty, N., Jarvis, A., 2020. The global divide in data-driven farming. Nat Sustain 4, 154–160. https://doi.org/10.1038/s41893-020-00631-0
Merlos, F.A., Hijmans, R.J., 2020. The scale dependency of spatial crop species diversity and its relation to temporal diversity 117, 26176–26182. https://doi.org/10.1073/pnas.2011702117/-/DCSupplemental
Miljkovic, D., 2005. Measuring and causes of inequality in farm sizes in the United States. Agricultural Economics 33, 21–27. https://doi.org/10.1111/j.1574-0862.2005.00303.x
Müller, M.F., Penny, G., Niles, M.T., Ricciardi, V., Chiarelli, D.D., Davis, K.F., Dell'Angelo, J., D'Odorico, P., Rosa, L., Rulli, M.C., Mueller, N.D., 2021. Impact of transnational land acquisitions on local food security and dietary diversity. Proceedings of the National Academy of Sciences 118. https://doi.org/10.1073/pnas.2020535118
Niether, W., Jacobi, J., Blaser, W.J., Andres, C., Armengot, L., 2020. Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. Environmental Research Letters 15, 104085. https://doi.org/10.1088/1748-9326/abb053
Nkebiwe, P.M., Weinmann, M., Bar-Tal, A., Müller, T., 2016. Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis. Field Crops Res 196, 389–401. https://doi.org/10.1016/j.fcr.2016.07.018
Noack, F., Larsen, A., 2019. The contrasting effects of farm size on farm incomes and food production. Environmental Research Letters 14. https://doi.org/10.1088/1748-9326/ab2dbf
Noack, F., Larsen, A., Kamp, J., Levers, C., 2022. A bird's eye view of farm size and biodiversity: The ecological legacy of the iron curtain. Am J Agric Econ 104, 1460–1484. https://doi.org/10.1111/ajae.12274
Omotilewa, O.J., Jayne, T.S., Muyanga, M., Aromolaran, A.B., Liverpool-Tasie, L.S.O., Awokuse, T., 2021. A revisit of farm size and productivity: Empirical evidence from a wide range of farm sizes in Nigeria. World Dev 146. https://doi.org/10.1016/j.worlddev.2021.105592
Paul, M., wa Gĩthĩnji, M., 2018. Small farms, smaller plots: land size, fragmentation, and productivity in Ethiopia. Journal of Peasant Studies 45, 757–775. https://doi.org/10.1080/03066150.2016.1278365
Paut, R., Sabatier, R., Tchamitchian, M., 2019. Reducing risk through crop diversification: An application of portfolio theory to diversified horticultural systems. Agric Syst 168, 123–130. https://doi.org/10.1016/j.agsy.2018.11.002
Pekin, B.K., 2016. Anthropogenic and topographic correlates of natural vegetation cover within agricultural landscape mosaics in Turkey. Land use policy 54, 313–320. https://doi.org/10.1016/j.landusepol.2016.02.029
Prokopy, L.S., Floress, K., Arbuckle, J.G., Church, S.P., Eanes, F.R., Gao, Y., Gramig, B.M., Ranjan, P., Singh, A.S., 2019. Adoption of agricultural conservation practices in the United States: Evidence from 35 years of quantitative literature. J Soil Water Conserv 74, 520–534. https://doi.org/10.2489/jswc.74.5.520
Ramankutty, N., Ricciardi, V., Mehrabi, Z., Seufert, V., 2019. Trade-offs in the performance of alternative farming systems. Agricultural Economics 50, 97–105. https://doi.org/10.1111/agec.12534
Rapsomanikis, G., 2015. Food and Agriculture Organization of the United Nations Rome.
Ren, C., Jin, S., Wu, Y., Zhang, B., Kanter, D., Wu, B., Xi, X., Zhang, X., Chen, D., Xu, J., Gu, B., 2021. Fertilizer overuse in Chinese smallholders due to lack of fixed inputs. J Environ Manage 293. https://doi.org/10.1016/j.jenvman.2021.112913
Ren, C., Liu, S., van Grinsven, H., Reis, S., Jin, S., Liu, H., Gu, B., 2019. The impact of farm size on agricultural sustainability. J Clean Prod.

https://doi.org/10.1016/j.jclepro.2019.02.151
Ren, C., Zhang, X., Reis, S., Gu, B., 2022. Socioeconomic barriers of nitrogen management for agricultural and environmental sustainability. Agric Ecosyst Environ 333. https://doi.org/10.1016/j.agee.2022.107950
Ren, C., Zhang, X., Reis, S., Wang, S., Jin, J., Xu, J., Gu, B., 2023a. Climate change unequally affects nitrogen use and losses in global croplands. Nat Food 4, 294–304. https://doi.org/10.1038/s43016-023-00730-z
Ren, C., Zhou, X., Wang, C., Guo, Y., Diao, Y., Shen, S., Reis, S., Li, W., Xu, J., Gu, B., 2023b. Ageing threatens sustainability of smallholder farming in China. Nature 616, 96–103. https://doi.org/10.1038/s41586-023-05738-w
Ricciardi, V., Mehrabi, Z., Wittman, H., James, D., Ramankutty, N., 2021. Higher yields and more biodiversity on smaller farms. Nat Sustain 4, 651–657. https://doi.org/10.1038/s41893-021-00699-2
Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L., Chookolingo, B., 2018. How much of the world's food do smallholders produce? Glob Food Sec. https://doi.org/10.1016/j.gfs.2018.05.002
Rigg, J., Salamanca, A., Thompson, E.C., 2016. The puzzle of East and Southeast Asia's persistent smallholder. J Rural Stud 43, 118–133. https://doi.org/10.1016/j.jrurstud.2015.11.003
Rosa, L., Chiarelli, D.D., Sangiorgio, M., Beltran-Peña, A.A., Rulli, M.C., D'Odorico, P., Fung, I., 2020. Potential for sustainable irrigation expansion in a 3 °C warmer climate. Proceedings of the National Academy of Sciences 117, 29526–29534. https://doi.org/10.1073/pnas.2017796117
Rosa, L., Gabrielli, P., 2023. Achieving net-zero emissions in agriculture: a review. Environmental Research Letters 18. https://doi.org/10.1088/1748-9326/acd5e8
Rosa, L., Rulli, M.C., Ali, S., Chiarelli, D.D., Dell'Angelo, J., Mueller, N.D., Scheidel, A., Siciliano, G., D'Odorico, P., 2021. Energy implications of the 21st century agrarian transition. Nat Commun 12. https://doi.org/10.1038/s41467-021-22581-7
Rosa-Schleich, J., Loos, J., Mußhoff, O., Tscharntke, T., 2019. Ecological-economic trade-offs of Diversified Farming Systems – A review. Ecological Economics 160, 251–263. https://doi.org/10.1016/j.ecolecon.2019.03.002
Ruzzante, S., Labarta, R., Bilton, A., 2021. Adoption of agricultural technology in the developing world: A meta-analysis of the empirical literature. World Dev 146. https://doi.org/10.1016/j.worlddev.2021.105599
Samberg, L.H., Gerber, J.S., Ramankutty, N., Herrero, M., West, P.C., 2016. Subnational distribution of average farm size and smallholder contributions to global food production. Environmental Research Letters 11, 124010. https://doi.org/10.1088/1748-9326/11/12/124010
Schellhorn, N.A., Gagic, V., Bommarco, R., 2015. Time will tell: resource continuity bolsters ecosystem services. Trends Ecol Evol 30, 524–530. https://doi.org/10.1016/j.tree.2015.06.007
Shahmohamadloo, R.S., Febria, C.M., Fraser, E.D.G., Sibley, P.K., 2022. The sustainable agriculture imperative: A perspective on the need for an agrosystem approach to meet the United Nations Sustainable Development Goals by 2030. Integr Environ Assess Manag 18, 1199–1205. https://doi.org/10.1002/ieam.4558
Sibhatu, K.T., Krishna, V. V., Qaim, M., 2015. Production diversity and dietary diversity in smallholder farm households. Proc Natl Acad Sci U S A 112, 10657–10662. https://doi.org/10.1073/pnas.1510982112
Sirami, C., Gross, N., Baillod, A.B., Bertrand, C., Carrié, R., Hass, A., Henckel, L., Miguet, P.,

Vuillot, C., Alignier, A., Girard, J., Batáry, P., Clough, Y., Violle, C., Giralt, D., Bota, G., Badenhausser, I., Lefebvre, G., Gauffre, B., Vialatte, A., Calatayud, F., Gil-Tena, A., Tischendorf, L., Mitchell, S., Lindsay, K., Georges, R., Hilaire, S., Recasens, J., Solé-Senan, X.O., Robleño, I., Bosch, J., Barrientos, J.A., Ricarte, A., Marcos-Garcia, M.Á., Miñano, J., Mathevet, R., Gibon, A., Baudry, J., Balent, G., Poulin, B., Burel, F., Tscharntke, T., Bretagnolle, V., Siriwardena, G., Ouin, A., Brotons, L., Martin, J.L., Fahrig, L., 2019. Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions. Proc Natl Acad Sci U S A 116, 16442–16447. https://doi.org/10.1073/pnas.1906419116

Skaggs, R.K., Samani, Z., 2005. Farm size, irrigation practices, and on-farm irrigation efficiency. Irrigation and Drainage 54, 43–57. https://doi.org/10.1002/ird.148

Smith, O.M., Kennedy, C.M., Owen, J.P., Northfield, T.D., Latimer, C.E., Snyder, W.E., 2020. Highly diversified crop–livestock farming systems reshape wild bird communities. Ecological Applications 30. https://doi.org/10.1002/eap.2031

Steinmann, H.-H., Dobers, E.S., 2013. Spatio-temporal analysis of crop rotations and crop sequence patterns in Northern Germany: potential implications on plant health and crop protection. Journal of Plant Diseases and Protection 120, 85–94. https://doi.org/10.1007/BF03356458

Su, H., Willaarts, B., Luna-Gonzalez, D., Krol, M.S., Hogeboom, R.J., 2022. Gridded 5 arcmin datasets for simultaneously farm-size-specific and crop-specific harvested areas in 56 countries. Earth Syst Sci Data 14, 4397–4418. https://doi.org/10.5194/essd-14-4397-2022

Sumner, D.A., 2014. American farms keep growing: Size, productivity, and policy. Journal of Economic Perspectives 28, 147–166. https://doi.org/10.1257/jep.28.1.147

Tan, M., Robinson, G.M., Li, X., Xin, L., 2013. Spatial and temporal variability of farm size in China in context of rapid urbanization. Chin Geogr Sci 23, 607–619. https://doi.org/10.1007/s11769-013-0610-0

Tan, S., Heerink, N., Qu, F., 2006. Land fragmentation and its driving forces in China. Land use policy 23, 272–285. https://doi.org/10.1016/j.landusepol.2004.12.001

Timmons, D., Wang, Q., 2010. Direct food sales in the united states: Evidence from state and county-level data. Journal of Sustainable Agriculture 34, 229–240. https://doi.org/10.1080/10440040903482605

Tittonell, P., Giller, K.E., 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. Field Crops Res 143, 76–90. https://doi.org/10.1016/j.fcr.2012.10.007

Toledo-Hernández, M., Tscharntke, T., Tjoa, A., Anshary, A., Cyio, B., Wanger, T.C., 2021. Landscape and farm-level management for conservation of potential pollinators in Indonesian cocoa agroforests. Biol Conserv 257, 109106. https://doi.org/10.1016/j.biocon.2021.109106

Tscharntke, T., Grass, I., Wanger, T.C., Westphal, C., Batáry, P., 2021. Beyond organic farming – harnessing biodiversity-friendly landscapes. Trends Ecol Evol. https://doi.org/10.1016/j.tree.2021.06.010

Unay Gailhard, I., Bojnec, S., 2015. Farm size and participation in agri-environmental measures: Farm-level evidence from Slovenia. Land use policy 46, 273–282. https://doi.org/10.1016/j.landusepol.2015.03.002

U.S. Environmental Protection Agency, 2023. Basic Information about Nonpoint Source (NPS) Pollution, https://www.epa.gov/nps/basic-information-about-nonpoint-source-nps-pollution [WWW Document].

Valencia, V., Wittman, H., Blesh, J., 2019. Structuring Markets for Resilient Farming Systems. Agron Sustain Dev 39, 25. https://doi.org/10.1007/s13593-019-0572-4

Wang, C., Duan, J., Ren, C., Liu, H., Reis, S., Xu, J., Gu, B., 2022. Ammonia Emissions from

Croplands Decrease with Farm Size in China. Environ Sci Technol 56, 9915–9923. https://doi.org/10.1021/acs.est.2c01061

Wang, S., Bai, X., Zhang, X., Reis, S., Chen, D., Xu, J., Gu, B., 2021. Urbanization can benefit agricultural production with large-scale farming in China. Nat Food 2, 183–191. https://doi.org/10.1038/s43016-021-00228-6

Wang, Yan, Zhu, Y., Zhang, S., Wang, Yongqiang, 2018. What could promote farmers to replace chemical fertilizers with organic fertilizers? J Clean Prod 199, 882–890. https://doi.org/10.1016/j.jclepro.2018.07.222

Wu, Y., Xi, X., Tang, X., Luo, D., Gu, B., Lam, S.K., Vitousek, P.M., Chen, D., 2018. Policy distortions, farm size, and the overuse of agricultural chemicals in China. Proc Natl Acad Sci U S A 115, 7010–7015. https://doi.org/10.1073/pnas.1806645115

Zhang, C., Liu, S., Wu, S., Jin, S., Reis, S., Liu, H., Gu, B., 2019. Rebuilding the linkage between livestock and cropland to mitigate agricultural pollution in China. Resour Conserv Recycl 144, 65–73. https://doi.org/10.1016/j.resconrec.2019.01.011

Zhang, W., Cao, G., Li, X., Zhang, H., Wang, C., Liu, Q., Chen, X., Cui, Z., Shen, J., Jiang, R., Mi, G., Miao, Y., Zhang, F., Dou, Z., 2016. Closing yield gaps in China by empowering smallholder farmers. Nature 537, 671–674. https://doi.org/10.1038/nature19368

Zhang, W., Qian, C., Carlson, K.M., Ge, X., Wang, X., Chen, X., 2021. Increasing farm size to improve energy use efficiency and sustainability in maize production. Food Energy Secur 10. https://doi.org/10.1002/fes3.271

# Highlights

- The role of smallholders in food security and poverty alleviation.
- The importance of increasing farm size to medium scale.
- Cautions of risks of large-scale farming, such as biodiversity loss.
- Tailored strategies for sustainable farming of various sizes.

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: