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Higher yields and more biodiversity on smaller farms

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Small farms constitute most of the world's farms and are a central focus of sustainable agricultural development. However, the relationship between farm size and production, profitability, biodiversity and greenhouse gas emissions remains contested. Here, we synthesize current knowledge through an evidence review and meta-analysis and show that smaller farms, on average, have higher yields and harbour greater crop and non-crop biodiversity at the farm and landscape scales than do larger farms. We find little conclusive evidence for differences in resource-use efficiency, greenhouse gas emission intensity and profits. Our findings highlight the importance of farm size in mediating some environmental and social outcomes relevant to sustainable development. We identify a series of research priorities to inform land- and market-based policies that affect smallholders globally.

Farm size has become a key variable of interest in discussions surrounding food security, development, and the environment[1]. Most of the world's farms are small—of the 570 million farms in the world, 84% are <2 ha in size[2]. Smallholders are facing growing pressure on their livelihoods from low prices in global markets and climate change-induced production losses[3]. Accordingly, smallholders have been the target of global development policies such as the Sustainable Development Goal (SDG) target 2.3, which seeks to support smallholders by increasing their productivity, incomes, and access to land. Many countries' Intended Nationally Determined Contributions (INDCs) of the UN Conference of Parties on Climate Change (COP21) also aim to bolster smallholders' adaptive capacity.

Numerous scholars argue that smaller farms perform better than larger farms in terms of production, environmental, and socioeconomic outcomes[4]. On the basis of these arguments, scholars, policy makers, and social movements argue in favour of land reforms to redistribute farmland[5,6]. Although 84% of the world's farms are <2 ha in size, they only constitute 12% of farmland—increasing the proportion of farmland in smaller farms will arguably increase its benefits. At the same time, consumers have increased their willingness to pay for products with labels associated with smaller farms[7,8]. Thus, there is a growing call for support for small farms. While this support is important, the performance of small farms in terms of productivity, resource efficiency, biodiversity, and greenhouse gas (GHG) emissions has itself remained highly contested[9–14].

Here, we synthesize the relationship between farm size and six socioeconomic and environmental outcomes, leveraging the past 50 yr of empirical evidence that directly assessed crop production, environmental performance, and economic outcomes as they relate to farm size. Our systematic assessment of the multidimensional outcomes related to farm size builds on past reviews that focused on single outcomes (for example, yield, economic performance, or biodiversity metrics for specific species)[15–18], non-systematic reviews[15,16], studies based on indirect measurements of farm size and the outcome variables of interest[19–21], and studies with specific regional foci[15,17]. We present evidence from 118 studies (318 observations) from 51 countries on the relationship between relative farm size (along a continuum) and: (1) yields as value of crop output per area (value ha^{-1}) or total crop production per area (kg ha^{-1}), (2) crop diversity at species and varietal levels, (3) non-crop biodiversity at field and landscape levels, (4) resource-use efficiency as measured in terms of technical efficiency[22], (5) GHG emissions per unit output, and (6) profit per unit area.

Results

Our analysis finds that smaller farms have higher yields and harbour greater crop diversity and higher levels of non-crop biodiversity at the field and landscape scales than larger farms (Table 1). We find no conclusive evidence for a relationship between farm size and resource-use efficiency, GHG emissions, or profit. In the remainder of this article, we will address each of these key findings in turn and discuss their implications for policy initiatives and consumer support for small farms globally.

Smaller farms have higher yields. Our synthesis shows that, in the literature, when primary studies assess yield across farm sizes, 79% (95% confidence interval, CI = 58–100%) of them report that smaller farms have higher yields (in either weight ha^{-1} and value ha^{-1} terms) (Fig. 1). We also find that yields typically decrease by 5% for each hectare increase in farm size (−5% mean effect; 95% CI = −9 to −1%; Fig. 2a and Fig. 3), within the range of studied observations (mean = 7.5 ha; s.d. = 22.7 ha). While the distribution of effects includes deviant cases (Fig. 3 and Supplementary Fig. 1), these new findings show that, on average, the available evidence supports the idea—which originated in the 1920s and has been studied extensively since the 1960s—that smaller farms are higher yielding than larger farms[14,23,24]. Moreover, we find that controlling for labour removed the effect—our model not controlling for labour has stronger effect size (although not statistically different from zero at the 95% confidence level) than the one that does. This result is in line with Sen's 1964 prediction[24] and subsequent literature[25], that

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Table 1 | Main results and mechanisms

Variable	Result	Mechanisms favouring small farms	Mechanisms favouring large farms
Yield	Smaller farms have higher yields	Reliance on family labour (for example, Fig. 2).	Mechanization enables higher yields with less labour but is only cost-effective on larger fields[57].
Biodiversity (non-crop)	Smaller farms have higher biodiversity	Smaller fields have more edges that provide habitat[5,36,58]. Independently managed smaller fields and farms may create a more heterogeneous landscape[59].	The link between field and farm size is relatively understudied; large farms with small fields may also benefit biodiversity but this was untested in the reviewed literature.
Crop diversity	Smaller farms have higher crop diversity	Subsistence farmers plant a greater diversity of traditional crops to meet nutritional needs[30]. Small farms are incentivized to cultivate landraces when there are niche markets for traditional crops[31].	Varietal diversity requires a minimum amount of space to prevent genetic erosion for wind-pollinated crops[60,61]. Diversified crops can reduce long-term risk at the expense of short-term profit, which may require financial buffers[62,63].
Resource-use efficiency	Inconclusive evidence	In contexts where off-farm labour opportunities were greater, there was less available on-farm family labour and, in turn, greater technical efficiency[64].	Increased access to information from extension and advisory services was associated with greater technical efficiency, which is often only cost-effective on larger fields[64–67].
GHG emissions	Inconclusive evidence	Smaller farms may use less input-intensive production methods but this was untested in the reviewed literature.	Agricultural mechanization can enable higher yields with less input use, and mechanization is often only cost-effective on larger fields[57].
Profit	Inconclusive evidence	Specialty markets for traditional foods offer higher prices[31]. Smallholder credit access can increase access to inputs and markets[68].	Better market access for larger farms[69,70]. Recovering fixed costs requires a minimum scale[69,71]. Better access to land-based subsidies[72].

suggests that labour markets are an important reason for the inverse farm size–productivity relationship (Fig. 2b).

Smaller farms have greater crop diversity. While many field studies have explored in situ crop diversity on small farms[26–28], few directly measured the relationship between farm size and crop diversity. In our review, four studies show higher crop diversity on smaller farms, while three found the opposite; much too small a sample for statistical inference. But we previously conducted an in-depth quantitative analysis on the relationship between crop diversity and farm size across 55 countries and 154 crops using a newly harmonized dataset of nationality representative farmer surveys and agricultural censuses[29]. We found that, except for an unexplained dip in the 2–5 ha size range, there is a strong inverse relationship globally between farm size and the number of crop species found across the landscape—with higher species diversity within smaller farms than larger farms when controlling for area (Supplementary Fig. 2). Crop diversity on small farms is selected by farmers for a range of reasons such as improved nutrition[30], market diversification[31] and mitigation of drought risk[32].

Smaller farms harbour greater non-crop biodiversity. There are three key pathways by which smaller farms could be beneficial for non-crop biodiversity covered in the literature. The first is through ecological management practices, such as limited insecticide use and use of organic management practices. The second is through increased field edges (increased margin-to-field area ratio); increased field edges can lead to larger available breeding habitats for arthropods[33,34], provide refuge for arthropods and smaller species to colonize after escaping recently disturbed fields[35,36], increase the number of pollinators and beneficial predators within fields[4,34] and act as conservation corridors for arthropods and small mammals[37,38]. The third is through landscape composition, with small-farm-dominated landscapes harbouring diverse land cover types such as forests and wetlands, fields of different crops or fields in different phenological stages of production[39,40]. In the studies we reviewed, there is evidence for all of these effects. When combined,

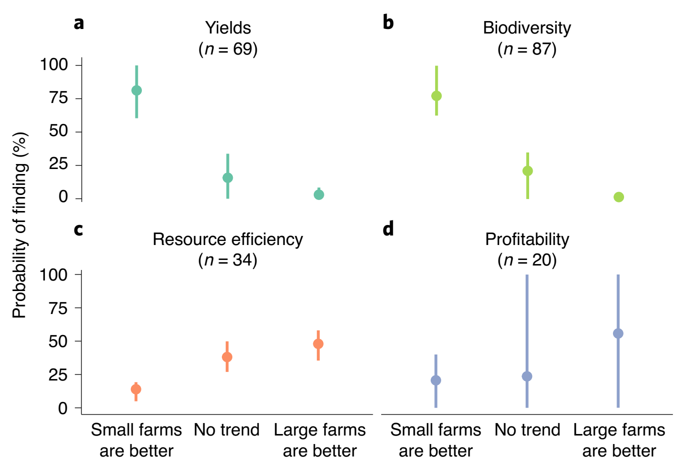

Fig. 1 | The probability of studies finding relationships between farm size and each outcome variable. Results are as per the vote count findings (for example, small farms have more biodiversity when compared to larger farms, compared to no trend emerging between farm size and profitability). **a–d**, Results are shown for the following outcome variables: yield (**a**), biodiversity (**b**), resource efficiency (**c**), and profitability (**d**). The average and 95% CIs are given (see Supplementary Table 3 for underlying data). Note, GHG emission studies were typically on individual farms so we could not conduct vote counts on this variable.

77% of studies (95% CI = 61–99%) reported that smaller farms and fields have greater biodiversity at the farm and landscape levels compared to larger farms and fields (Fig. 1).

The three remaining variables we tested—GHG emissions, resource-use efficiency, and profits—did not show conclusive relationships for the effect size magnitude and sign (Figs. 2, 4, and 5), even though the majority of studies concluded that larger farms had greater resource efficiency than smaller farms (Fig. 1). For example, while the evidence we reviewed shows that GHG

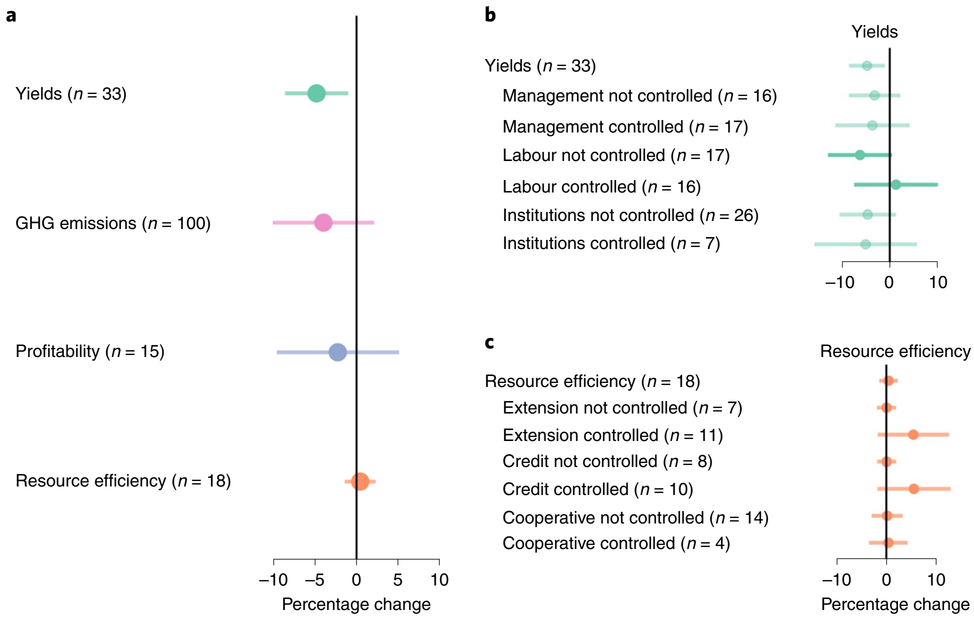

Fig. 2 | The pooled effect sizes for each outcome variable that show the percent change per 1 ha increase in farm size. a, Pooled effect size per variable as derived from the random effect meta-regressions. The vertical black line indicates the 1:1 response ratio where, for a 1-ha change in farm size, there is no change in the outcome variable. A response ratio <0 suggests that smaller farms have a higher effect (for example, smaller farms have higher yields) and, if it is >0, then larger farms have a higher effect. The number of observations (*n*) and 95% CIs are given per variable. **b**, For yield, sensitivity analyses fit separate models to explore heterogeneity in the effect for studies that controlled for common explanations for the inverse farm size–yield relationship: institutional characteristics, farm management and family labour. **c**, For resource-use efficiency, separate models were fit to test if the effect was moderated by common development interventions to improve smallholder resource-use efficiency: extension access, farmer cooperatives/groups, and credit access. Profit and GHG emissions had no additional models. Note, biodiversity studies typically did not include regression coefficients, so we could not conduct a random effects meta-regression. (See Supplementary Table 4 for underlying data).

emissions per unit output tend to be higher on smaller farms, suggesting that smaller farms might be less efficient per unit output, the confidence intervals around this effect crossed zero (−4% mean effect; 95% CI = −10–2%). We found no clear difference between small or large farms in technical efficiency (our proxy for resource efficiency per unit output with 0% mean effect; 95% CI = −1–2%), even after controlling for a variety of moderating factors, such as access to credit, extension services or cooperative membership (Fig. 2c). See the Supplementary Information for further discussion of these results. Similarly, while profitability per unit area also declined with increasing farm size, statistical confidence in the effect was also low (−2% mean effect; 95% CI = −10–5%) (Fig. 2a).

Discussion

Our evidence review and meta-analysis of the current evidence base for these six outcomes associated with farm size finds strong support for the inverse farm size–productivity and farm size–diversity relationship (empirical findings that both have strong theoretical support[24,41–43]). While a couple of emerging studies[44,45], with limited coverage, suggest that the inverse size–productivity relationship might simply be a result of measurement errors and while we were unable to rule out this possibility, our synthesis did find the inverse farm size–yield effect was removed when controlling for labour, suggesting that smaller farms may be more productive due to the availability of family labour[24]. Similarly, we recognize that socio-political context is important and small farms may not always be more biodiverse[46] but most of the evidence base across a broad geographic range of agricultural systems is in support of this positive relationship.

An important caveat to interpreting the past literature for each of these outcomes are regional biases and variation. Regional biases are most evident in the biodiversity literature that has predominantly focused on higher-income countries, mainly in North America and Europe (Supplementary Fig. 4). Different regions may contain species that prefer environments that larger farms foster, either through their larger fields or different farm management techniques (Table 1). While we could not test for these factors explicitly due to our sample size, a dominant theme in the literature for other indicators (yield, profitability, and resource efficiency) was that a farm's political, socioeconomic, and geographic context (a farmer's access to training, credit, machinery, insurance, inputs, markets, and/or subsidies) may explain the farm size to outcome relationships. For instance, the relationships between farm size, resource efficiency, and profit were the most spatially heterogeneous across all variables examined. For certain smallholder-dominant countries (for example, India and Ethiopia) we found that smaller farms were more profitable, whereas larger farms were more profitable in countries dominated by large farms, higher incomes, and better rural infrastructure (for example, the United States). This may suggest that smallholders have better access to markets, inputs, and technologies in a smallholder-dominant system that may affect their profitability and resource efficiency (see Supplementary Information for expanded discussion).

Systematic evidence syntheses, such as meta-analyses, are an iterative process[47]. For some of the outcomes (such as GHG emissions, profits, and resource-use efficiency) we were unable to identify consistent or confident outcomes from the existing literature. This may be due to the small number of included studies, limited cross-country analyses, or that these relationships are too context-specific to be generalized. Future work should continue to assess these outcomes and build on this study to include other important outcomes, such as mental and physical health of workers and farmers, employment opportunities, pesticide or fertilizer use efficiency, and other key ecosystem services, such as pollination, in

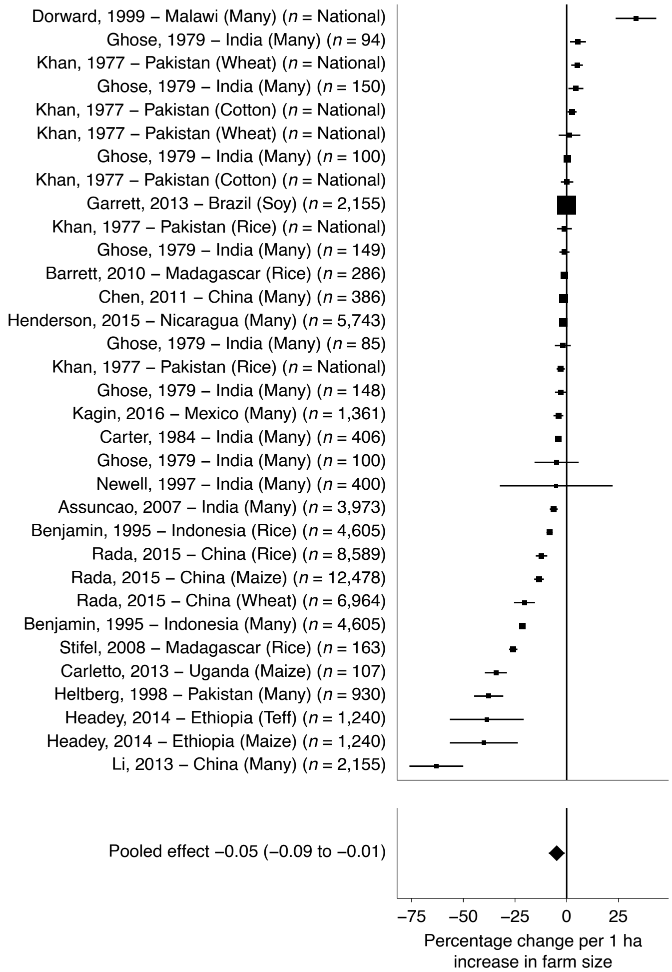

Fig. 3 | Forest plot for yields, where observations are in standardized form and 95% CI are given. The size of each point estimate relates to the inverse standard error. The pooled effect and 95% CI are given in the lower plot. The country, crop name, and sample size (*n*) for each observation are given on the *y* axis. 'National' sample sizes indicate that the author used tabulated national statistics and did not include the sample size. Please see the source data in the Supplementary Information for complete list of references shown in the figure.

addition to examining literature in languages other than English. New primary work is also needed to further explore the functional form of the effects we present here, and to explore how different socioecological and political conditions and measurement methods may mediate positive or negative outcomes across farm size classes. This could further inform policies on land reform (such as redistribution or consolidation) that address market failures so that such policies can maximize the multidimensional benefits of farming systems to society[48].

To support sustainable transitions in farming practices across a range of farm sizes, more evidence-based synthesis is needed at broad regional scales. Until recently, the role of farm size in the global food system has been largely assessed by independent case studies. As international commitments (for example, SDGs and COP21 INDCs) begin to evolve into actionable funding plans and as countries continue to decide on land use policies that directly affect the size of farms, it is critical to identify how farm size affects different social, economic and environmental outcomes.

Our study lends evidence to boost support for policies targeting smallholders. Most of the world's farms (84%) are operated by smallholders[2] and smallholders in lower-income countries are also among the poorest people on the planet[49]. Our study shows that smallholders are both productive and stewards of biodiversity. Rewarding smaller farms for their conservation benefits may be one policy pathway towards supporting smallholders. Biodiversity could be promoted on larger farms by promoting more ecologically friendly management practices and increasing biodiversity refuges such as buffer strips and increased natural perimeters.

These findings come at a time where donor countries need to invest an estimated US$14 billion annually to achieve the goal of SDG 2.3 to double the incomes and productivity of smallholders[49]. Our review adds to the motivation for these investments. We found that, despite smallholders' increased yields and role in provision of ecosystem services, there is not enough evidence for equivalent gains in smallholders' profits. Thus, development support for smallholders is imperative from multiple viewpoints: the data not only show that investing in smallholders could lead to humanitarian benefits but also to increases in food production and benefits to biodiversity.

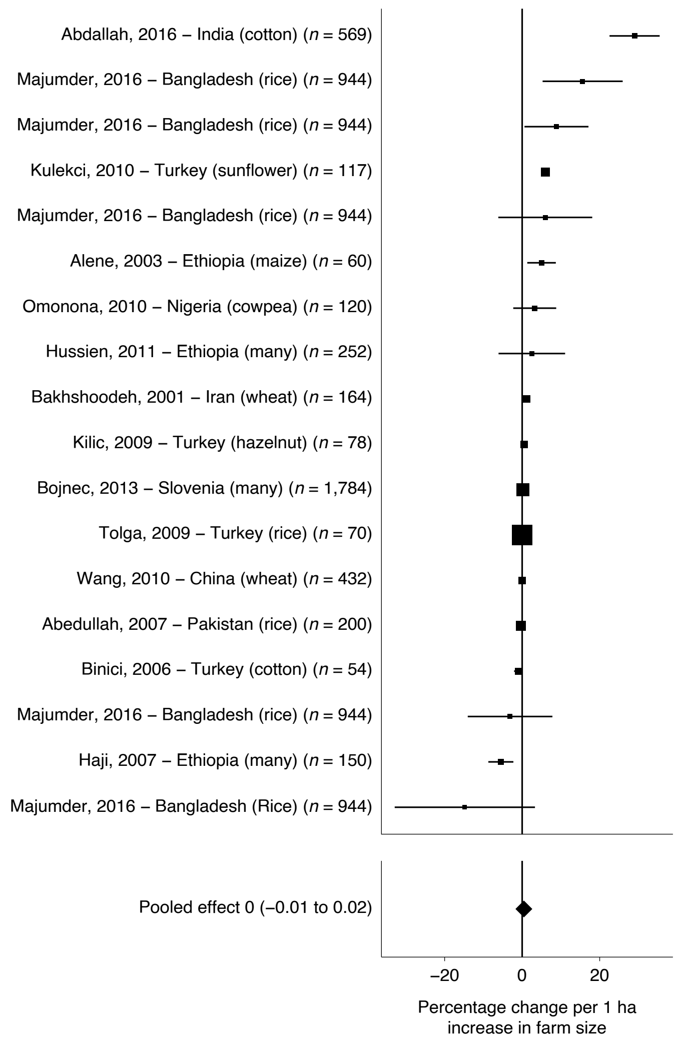

Fig. 4 | Forest plot for resource efficiency, where observations are in standardized form and 95% CI are given. The size of each point estimate relates to the inverse standard error. The pooled effect and 95% CI are given in the lower plot. The country, crop name, and sample size (*n*) for each observation are given on the *y* axis. 'National' sample sizes indicate that the author used tabulated national statistics and did not include the sample size. Please see the source data in the Supplementary Information for complete list of references shown in the figure.

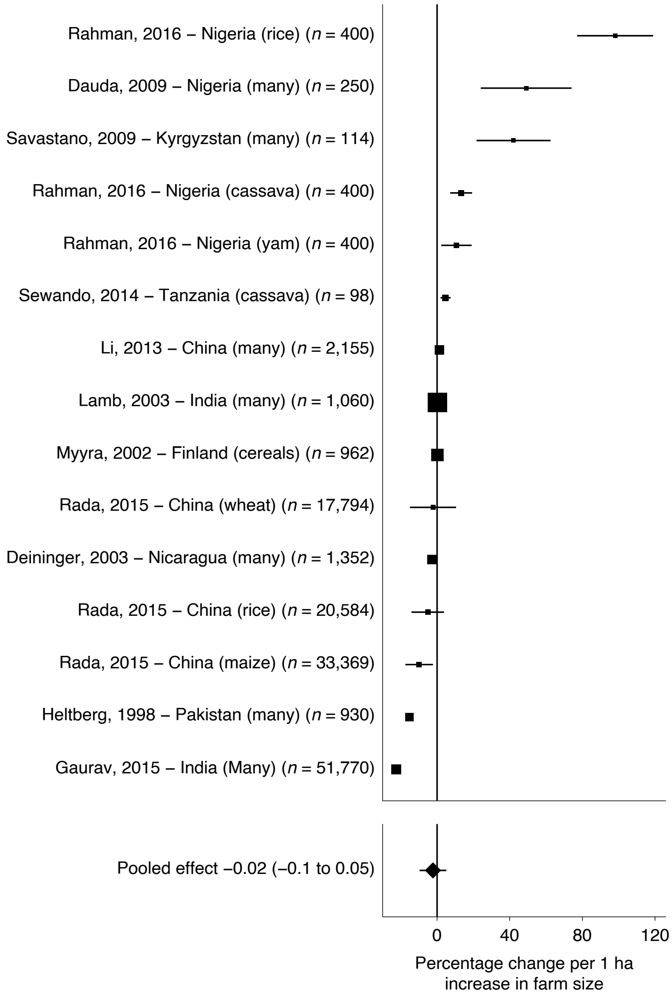

Fig. 5 | Forest plot for profitability, where observations are in standardized form and 95% CI are given. The size of each point estimate relates to the inverse standard error. The pooled effect and 95% CI are given in the lower plot. The country, crop name, and sample size (*n*) for each observation are given on the *y* axis. Please see the source data in the Supplementary Information for complete list of references shown in the figure.

Such a triple reward confirms that support for smallholders globally is an essential pathway for sustainable development.

Methods

A meta-analysis was conducted using the PRISMA guidelines[50] (see Supplementary Fig. 3 for inclusions/omissions and Supplementary Table 1 for Boolean search terms). Below, we outline our data collection and synthesis methods.

Data. We searched the Web of Science and Scopus databases for studies in English published before December 2017. We used four inclusion criteria: (1) peer-reviewed; (2) directly measured farm size and the outcome variable(s) of interest; (3) reported error estimates/significance tests in determining effect size; and (4) compared farms with similar management systems (for example, compared small and large cereal farms, not small vegetable farms to large cereal farms) or controlled for the cropping systems' differences (for example, converted different crops to their value amount and/or controlled for the different types of crop species planted). The inclusion of studies that compared farms with similar management systems enabled us to examine if policies should target certain farm sizes to grow particular crops. Future research may want to omit this inclusion criteria to examine policy questions relevant to which types of crops should a country grow given their farm size distribution.

Studies were coded at the observational level to analyse multiple crops, years and locations per study; studies had multiple observations if they separately reported different crops, years and/or locations per outcome variable. The main conclusions were categorically coded as vote counts, where an increase in farm size was associated with a decrease, increase or null relationship to the variable of interest (we found no nonlinear results in the literature). For yield, resource-use efficiency and profit, we extracted several additional variables to calculate pooled effect sizes of regression model coefficients. To augment the sparse crop diversity and GHG emission literature on farm size, we used results from Ricciardi et al.[29] and Clark & Tilman's (2017)[51] dataset, respectively. We leveraged the Clark & Tilman meta-analysis database containing 742 agricultural life-cycle analysis observations from 152 unique studies[51]; we coded observations that reported average farm size to construct a dataset containing crop species, GHG emissions per unit output (in CO_2 equivalents), average farm size and sample size for 100 observations (11 studies) that met our inclusion criteria. As part of our systematic assessment we extracted information from the broader literature on causal mechanisms behind the main trends, as well as factors that caused deviations from the main trends (Table 1).

Our search yielded 1,474 studies. In total, we identified 118 studies (318 observations) that met our inclusion criteria. From these, we included seven solely in the life-cycle analysis and coded 111 studies (218 observations) as vote counts, of which we extracted regression coefficients from 40 studies (66 observations) (Supplementary Table 2 shows summary statistics).

Synthesis of results. We ran three types of meta-regressions to synthesize the vote count findings, extracted regression slopes and the GHG emission estimates. Due to differing data availability across variables (for example, biodiversity studies did not typically report regression coefficients), not all variables were analysed in each meta-regression. First, we used cumulative link multilevel models (CLMM) to synthesize the ordinal vote count findings for yield, resource-use efficiency, profit and biodiversity[52,53]. We used CLMMs to examine the probability of the ordinal outcome variable (observation finding negative, null or positive relationships with farm size). For all CLMM and subsequent models (detailed in the following paragraphs), we set the study as a random effect. Hierarchical models are commonplace in meta-analyses and applied in our study because of the a priori expectation that observations within studies and across similar crop types would be correlated in the response, with random effects allowing us to account for non-independence. In addition, as used in meta-analyses, random effects estimate a variance component in addition to the sampling variance that fixed effects models assume; this extra variance component has enabled meta-analyses using random effects to be applied more generally and allows data to be interpreted as a random population of outcomes instead of a single 'true effect', as is a common interpretation of fixed effects meta-analyses[47]. For yields and non-crop biodiversity, we also set crop type as random effects. For non-crop biodiversity, we also set non-crop species type as a random effect. We tested if the additional random effects used for yields and non-crop biodiversity changed the results compared to using only studies as random effects and found no differences in our conclusions.

Second, we used hierarchical meta-regressions of the standardized regression slopes and standard errors[54,55] to calculate pooled effects for yield, resource-use efficiency and profit. Since certain variables contained multiple currencies, efficiency units or measurement metrics, we relied on the Rodríguez-Barranco et al. technique to convert farm size regression coefficients and standard errors into standardized regression coefficients[56]. Our standardized coefficients represent a relative change in the outcome variable per 1-ha change in farm size (we note that these coefficients are limited by the range of the underlying farm sizes in each study and should not be extrapolated). We used a linear model to synthesize results because the literature predominantly provided linear coefficients. We used the same random effects variable set up as in the CLMM models. Sensitivity tests were conducted through cumulative meta-regressions for continuous variables (for example, year of study and average farm size study observed) and subsetted meta-regression for categorical variables (for example, type of diversity metric used, if yield was defined by weight ha^{-1} or value ha^{-1}, if resource efficiency was derived from data envelopment analysis or stochastic frontier and so on). All sensitivity tests found no differences in results. Forest plots are given in Figs. 3–5. An inclusion of bias analysis was conducted through funnel plots that compare the observed outcomes to standard errors. There were no clear biases for yields and resource efficiency but a slight positive bias for profit (Supplementary Fig. 5).

This meta-regression framework also enabled us to further test if the variation in findings between different studies could be attributed to the inclusion/omission of variables that authors used when estimating the relationship between farm size and the variable of interest, through sensitivity analyses using moderators. For yield, we assessed the importance of moderators such as the types of production methods, institutional characteristics (credit markets and access, extension access and involvement in farmer cooperatives) and types of labour (general labour market imperfections, family labour and household size). Our logic was that, if the relationship is moderated by these factors (for example, if the main relationship became null), it would indicate that there is a systematic variable omission bias in the literature that, once corrected for, could explain the inverse farm size to yield relationship. For resource-use efficiency, we conducted similar sensitivity analyses, by including moderators that described development interventions (credit access, extension access or farmer group membership). Our key hypothesis was that having similar access to credit, extension or inputs and markets (through farmer groups) may enable small farms to be equally or more efficient than large farms.

Third, for the GHG emission observations, we used robust linear mixed-effects models where we set the study and crop type as random effects. To estimate GHG emissions per unit output, we used the log average farm size of a study as a fixed effect. The key difference in the GHG emission model is that the data are at the aggregated farm level, as opposed to extracted regression coefficients for the yield, resource-use efficiency and profit models. (Formulas and further detail on each meta-regression used are available in the Supplementary information.)

Data availability

The data that support the findings of this study are available in the Supplementary Information. Source data are provided with this paper.

Code availability

The computer code that support the findings of this study is available in the Supplementary Information.

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References

1. Meyfroidt, P. Mapping farm size globally: benchmarking the smallholders debate. *Environ. Res. Lett.* **12**, 10–13 (2017).
2. Lowder, S. K., Skoet, J. & Raney, T. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Dev.* **87**, 16–29 (2016).
3. *Food Security and Nutrition in the World* (FAO, 2018).
4. Belfrage, K., Björklund, J. & Salomonsson, L. The effects of farm size and organic farming on diversity of birds, pollinators, and plants in a Swedish landscape. *Ambio* **34**, 582–588 (2005).
5. Rosset, P. Re-thinking agrarian reform, land and territory in La Via Campesina. *J. Peasant Stud.* **40**, 721–775 (2013).
6. Borras, S. M. in *Transnational Agrarian Movements Confronting Globalization* (Borras, S. M. et al.) 91–121 (Wiley-Blackwell, 2008).
7. Meas, T., Hu, W., Batte, M. T., Woods, T. A. & Ernst, S. Substitutes or complements? Consumer preference for local and organic food attributes. *Am. J. Agric. Econ.* **97**, 1044–1071 (2015).
8. Moon, W. & Pino, G. Do U.S. citizens support government intervention in agriculture? Implications for the political economy of agricultural protection. *Agric. Econ.* **49**, 119–129 (2018).
9. Altieri, M. A. *Small Farms as a Planetary Ecological Asset: Five Key Reasons Why We Should Support the Revitalisation of Small farms in the Global South* (Third World Network, 2008).
10. Konvicka, M., Benes, J. & Polakova, S. Smaller fields support more butterflies: comparing two neighbouring European countries with different socioeconomic heritage. *J. Insect Conserv.* **20**, 1113–1118 (2016).
11. Haji, J. Production efficiency of smallholders' vegetable-dominated mixed farming system in eastern Ethiopia: a non-parametric approach. *J. Afr. Econ.* **16**, 1–27 (2007).
12. Barrett, C. B., Bellemare, M. F. & Hou, J. Y. Reconsidering conventional explanations of the inverse productivity–size relationship. *World Dev.* **38**, 88–97 (2010).
13. Sen, A. K. An aspect of Indian agriculture. *Econ. Wkly* **14**, 243–246 (1962).
14. Chayanov, A. V. V. *The Theory of Peasant Cooperatives* (Ohio State Univ. Press, 1926).
15. Otsuka, K., Liu, Y. & Yamauchi, F. Growing advantage of large farms in Asia and its implications for global food security. *Glob. Food Sec.* **11**, 5–10 (2016).
16. Rada, N. E. & Fuglie, K. O. New perspectives on farm size and productivity. *Food Policy* **84**, 147–152 (2019).
17. Smith, R. K., Jennings, N. V., & Harris, S. A quantitative analysis of the abundance and demography of European hares *Lepus europaeus* in relation to habitat type, intensity of agriculture and climate. *Mammal Rev.* **35**, 1–24 (2005).
18. Rudel, T. et al. Do smallholder, mixed crop-livestock livelihoods encourage sustainable agricultural practices? A meta-analysis. *Land* **5**, 6 (2016).
19. Cohn, A. S. et al. Smallholder agriculture and climate change. *Annu. Rev. Environ. Resour.* **42**, 347–375 (2017).
20. Graeub, B. E. et al. The state of family farms in the world. *World Dev.* **87**, 1–15 (2016).
21. Ebel, R. Are small farms sustainable by nature? Review of an ongoing misunderstanding in agroecology. *Challenges Sustain.* **8**, 17–29 (2020).
22. De Koeijer, T. J., Wossink, G. A. A., Struik, P. C. & Renkema, J. A. Measuring agricultural sustainability in terms of efficiency: the case of Dutch sugar beet growers. *J. Environ. Manag.* **66**, 9–17 (2002).
23. Barrett, C. B., Bellemare, M. F. & Hou, J. Y. Reconsidering conventional explanations of the inverse productivity size relationship. *World Dev.* **38**, 88–97 (2010).
24. Sen, A. K. Size of holdings and productivity. *Econ. Wkly* **16**, 323–326 (1964).
25. Dorward, A. Agricultural labour productivity, food prices and sustainable development impacts and indicators. *Food Policy* **39**, 40–50 (2013).
26. Zimmerer, K. S. Geographies of seed networks for food plants (potato, Ulluco) and approaches to agrobiodiversity conservation in the Andean countries. *Soc. Nat. Resour. Int. J.* **16**, 583–601 (2011).
27. Bicksler, A. et al. Methodologies for strengthening informal indigenous vegetable seed systems in northern Thailand and Cambodia. *Acta Hortic.* **958**, 67–74 (2012).
28. Coomes, O. T. et al. Farmer seed networks make a limited contribution to agriculture? Four common misconceptions. *Food Policy* **56**, 41–50 (2015).
29. Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L. & Chookolingo, B. How much of our world's food do smallholders produce? *Glob. Food Sec.* **17**, 64–72 (2018).
30. Fifanou, V. G., Ousmane, C., Gauthier, B. & Brice, S. Traditional agroforestry systems and biodiversity conservation in Benin (West Africa). *Agrofor. Syst.* **82**, 1–13 (2011).
31. Keleman, A., Hellin, J. & Flores, D. Diverse varieties and diverse markets: scale-related maize 'profitability crossover' in the central Mexican highlands. *Hum. Ecol.* **41**, 683–705 (2013).
32. McCord, P. F., Cox, M., Schmitt-Harsh, M. & Evans, T. Crop diversification as a smallholder livelihood strategy within semi-arid agricultural systems near Mount Kenya. *Land Use Policy* **42**, 738–750 (2015).
33. Jonsen, I. D. & Fahrig, L. Response of generalist and specialist insect herbivores to landscape spatial structure. *Landsc. Ecol.* **12**, 185–197 (1997).
34. Ahrenfeldt, E. J. et al. Pollinator communities in strawberry crops—variation at multiple spatial scales. *Bull. Entomol. Res.* **105**, 497–506 (2015).
35. Concepción, E. D., Fernandez-González, F. & Díaz, M. Plant diversity partitioning in Mediterranean croplands: effects of farming intensity, field edge, and landscape context. *Ecol. Appl.* **22**, 972–981 (2012).
36. Bravo-Monroy, L., Tzanopoulos, J. & Potts, S. G. G. Ecological and social drivers of coffee pollination in Santander, Colombia. *Agric. Ecosyst. Environ.* **211**, 145–154 (2015).
37. Horgan, F. G. Invasion and retreat: shifting assemblages of dung beetles amidst changing agricultural landscapes in central Peru. *Biodivers. Conserv.* **18**, 3519–3541 (2009).
38. Schai-Braun, S. C. & Hacklander, K. Home range use by the European hare (*Lepus europaeus*) in a structurally diverse agricultural landscape analysed at a fine temporal scale. *Acta Theriol.* **59**, 277–287 (2014).
39. Lovell, S. T., Mendez, V. E., Erickson, D. L., Nathan, C. & DeSantis, S. Extent, pattern, and multifunctionality of treed habitats on farms in Vermont, USA. *Agrofor. Syst.* **80**, 153–171 (2010).
40. Pekin, B. K. Anthropogenic and topographic correlates of natural vegetation cover within agricultural landscape mosaics in Turkey. *Land Use Policy* **54**, 313–320 (2016).
41. Chand, R., Prasanna, P. A. L. & Singh, A. Farm size and productivity: understanding the strengths of smallholders and improving their livelihoods. *Econ. Polit. Wkly* **54**, 5–11 (2011).
42. Dorward, A. Farm size and productivity in malawian smallholder agriculture. *J. Dev. Stud.* **35**, 141–161 (1999).
43. Kremen, C. Reframing the land-sparing/land-sharing debate for biodiversity conservation. *Ann. NY Acad. Sci.* **1355**, 52–76 (2015).
44. Carletto, C., Savastano, S. & Zezza, A. Fact or artifact: the impact of measurement errors on the farm size–productivity relationship. *J. Dev. Econ.* **103**, 254–261 (2013).
45. Abay, K. A., Abate, G. T., Barrett, C. B. & Tanguy, B. Correlated non-classical measurement errors, 'second best' policy inference and the inverse size–productivity relationship in agriculture. *J. Dev. Econ.* **139**, 171–184 (2019).
46. Hanesen, Z. K., Libecap, G. D., Hansen, Z. K. & Libecap, G. D. Small farms, externalities, and the Dust Bowl of the 1930s. *J. Polit. Econ.* **112**, 665–694 (2004).
47. Gurevitch, J., Koricheva, J., Nakagawa, S. & Stewart, G. Meta-analysis and the science of research synthesis. *Nature* **555**, 175–182 (2018).
48. Garibaldi, L. A. et al. Policies for ecological intensification of crop production. *Trends Ecol. Evol.* **34**, 282–286 (2019).
49. Laborde Debucquet, D., Murphy, S., Parent, M., Porciello, J. & Smaller, C. *Ceres2030: Sustainable Solutions to End Hunger Summary Report* (International Institute for Sustainable Development (IISD), 2020); https://hdl.handle.net/1813/72799
50. Moher, D., Liberati, A., Tetzlaff, J. & Altman, D. G. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Br. Med. J.* **339**, b2535 (2009).
51. Clark, M. & Tilman, D. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environ. Res. Lett.* **12**, 064016 (2017).
52. Agresti, A. *Categorical Data Analysis* (Wiley, 2002).
53. Christensen, R. H. B. Analysis of ordinal data with cumulative link models—estimation with the R-package ordinal. R-package version 28 (2015).
54. Becker, B. J. & Wu, M.-J. The synthesis of regression slopes in meta-analysis. *Stat. Sci.* **22**, 414–429 (2007).

55. Viechtbauer, W. Conducting meta-analyses in R with the metafor package. *J. Stat. Softw.* https://www.jstatsoft.org/article/view/v036i03 (2015).
56. Rodríguez-Barranco, M., Tobías, A., Redondo, D., Molina-Portillo, E. & Sánchez, M. J. Standardizing effect size from linear regression models with log-transformed variables for meta-analysis. *BMC Med. Res. Methodol.* **17**, 44 (2017).
57. Batte, M. T. & Ehsani, M. R. The economics of precision guidance with auto-boom control for farmer-owned agricultural sprayers. *Comput. Electron. Agric.* **53**, 28–44 (2006).
58. Ouin, A. & Burel, F. Influence of herbaceous elements on butterfly diversity in hedgerow agricultural landscapes. *Agric. Ecosyst. Environ.* **93**, 45–53 (2002).
59. Brown, P. W. & Schulte, L. A. Agricultural landscape change (1937–2002) in three townships in Iowa, USA. *Landsc. Urban Plan.* **100**, 202–212 (2011).
60. Teshome, A., Patterson, D., Asfaw, Z., Dalle, S. & Torrance, J. K. Changes of *Sorghum bicolor* landrace diversity and farmers' selection criteria over space and time, Ethiopia. *Genet. Resour. Crop Evol.* **63**, 55–77 (2016).
61. Gedebo, A., Appelgren, M., Bjornstad, A. & Tsegaye, A. Analysis of indigenous production methods and farm-based biodiversity of amochi (*Arisaema schimperian*, Schott) in two sub-zones of Southern Ethiopia. *Genet. Resour. Crop Evol.* **54**, 1429–1436 (2007).
62. Assunção, J. J. & Braido, L. H. B. Testing household-specific explanations for the inverse productivity relationship. *Am. J. Agric. Econ.* **89**, 980–990 (2007).
63. Altman, D. G. et al. Predictors of crop diversification: a survey of tobacco farmers in North Carolina (USA). *Tob. Control* **7**, 376–382 (1998).
64. Külekçi, M. Technical efficiency analysis for oilseed sunflower farms: a case study in Erzurum, Turkey. *J. Sci. Food Agric.* **90**, 1508–1512 (2010).
65. Latruffe, L., Balcombe, K., Davidova, S. & Zawalinska, K. Technical and scale efficiency of crop and livestock farms in Poland: does specialization matter? *Agric. Econ.* **32**, 281–296 (2005).
66. Ullah, A. & Perret, S. R. Technical- and environmental-efficiency analysis of irrigated cotton-cropping systems in Punjab, Pakistan using data envelopment analysis. *Environ. Manag.* **54**, 288–300 (2014).
67. Binici, T., Zulauf, C. R., Kacira, O. O. & Karli, B. Assessing the efficiency of cotton production on the Harran Plain, Turkey. *Outlook Agric.* **35**, 227–232 (2006).
68. Deininger, K., Zegarra, E. & Lavadenz, I. Determinants and impacts of rural land market activity: evidence from Nicaragua. *World Dev.* **31**, 1385–1404 (2003).
69. Deininger, K. & Byerlee, D. The rise of large farms in land abundant countries: do they have a future? *World Dev.* **40**, 701–714 (2012).
70. Alene, A. D. & Hassan, R. M. The determinants of farm-level technical efficiency among adopters of improved maize production technology in western Ethiopia. *Agrekon* **42**, 1–14 (2003).
71. Stifel, D. & Minten, B. Isolation and agricultural productivity. *Agric. Econ.* **39**, 1–15 (2008).
72. Rada, N., Wang, C. & Qin, L. Subsidy or market reform? Rethinking China's farm consolidation strategy. *Food Policy* **57**, 93–103 (2015).

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Author contributions

V.R., N.R. and H.W. conceived the idea and designed the data collection process. V.R. collected and coded the data. V.R., Z.M. and N.R. designed the analysis. V.R. and Z.M. conducted the analysis. V.R., Z.M., N.R., H.W. and D.J. contributed interpretations of results. All authors wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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