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How much of the world's food do smallholders produce?

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ABSTRACT

The widely reported claim that smallholders produce 70–80% of the world's food has been a linchpin of agricultural development policy despite limited empirical evidence. Recent empirical attempts to reinvestigate this number have lacked raw data on how much food smallholders produce, and have relied on model assumptions with unknown biases and with limited spatial and commodity coverage. We examine variations in crop production by farm size using a newly-compiled global sample of subnational level microdata and agricultural censuses covering more countries (n = 55) and crop types (n = 154) than assessed to date. We estimate that farms under 2ha globally produce 28–31% of total crop production and 30–34% of food supply on 24% of gross agricultural area. Farms under 2ha devote a greater proportion of their production to food, and account for greater crop diversity, while farms over 1000ha have the greatest proportion of post-harvest loss.

1. Introduction

It has been widely reported that smallholder farmers (defined generally as being less than 2 ha) produce 70–80% of the world's food ETC, 2009; Maass Wolfenson, 2013; FAO, 2014), are central to conserving crop diversity (Altieri, 2008; Badstue et al., 2005; Conway, 2011), produce more food crops than larger farms (Horrigan et al., 2002; Naylor et al., 2005), and yet are largely food insecure (IFAD and UNEP, 2013). These arguments have been a linchpin in recent agricultural development policy. For example, in 2014, the 'International Year of the Family Farm', the United Nations (UN) and other food security agencies reiterated these arguments to garner increased support for family farmers, who are predominantly smallholders (FAO, 2014). The COP21 agreement (the 2015 UN Conference of Parties on Climate Change) includes mitigation and adaptation commitments pertaining to agriculture from 179 countries that include the need to bolster smallholder adaptive capacity to climate change. Goal 2 of the UN Sustainable Development Goals (SDGs) aims to end hunger and achieve food security through sustainable agriculture; a key target (SDG 2.3) is by '2030, [to] double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists, and fishers' (UN, 2015). Yet, despite progress in steering development policy towards smallholder farmers, there is scant empirical data on smallholder farms, and their role in the food system.

Key to enacting and monitoring progress on these international agreements and policies is a global baseline on the contribution of smallholders to global food production and security. However, the data underlying three widely reported claims on smallholder crop production remain non-transparent or contradictory. First, the source of various UN reports citing smallholder production is a communiqué from the ETC group (ETC, 2009), which suggests that 'peasants' grow at least 70% of the world's food; yet, the derivation of the estimate is obscure in this report. Second, the claim that smaller farms produce more food directly consumed by people, with larger industrialized farms producing more non-food crops, such as biofuels and animal feed (Horrigan et al., 2002; Naylor et al., 2005), has been brought into question by the observation that smaller farms have larger amounts of post-harvest loss due to lack of market and cold storage access (Hodges et al., 2011; Tefera, 2012). Thirdly, while some authors argue that economies of scale are needed for farms to produce a diversity of crops (Rahman and Kazal, 2015), others suggest that larger farms face labor constraints that hamper mixed-cropping systems (Van den Berg et al., 2007), so it is unknown if smaller farms produce a greater diversity of crop species than larger farms. In sum, our current understanding how much food smallholders produce, what kinds of food they produce, where their food is destined in the food system, and how much nutrition it contains, are all key knowledge gaps in global agricultural research.

The need to fill these knowledge gaps has been recently recognized by scientists (Graeub et al. (2016); Herrero et al. (2017); Lowder et al. (2016); Samberg et al., 2016 (referred to as Graeub, Lowder, Herrero,

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and Samberg respectively hereafter). In 2016, a pair of studies evaluated the contribution of smallholders and family farms to global crop and food production. Lowder was the first to report on global farm size trends from 1960 to 2010 derived from 167 countries in the World Census of Agriculture (WCA). They found that small-farms (defined as being < 2 ha) constituted only 12% of the global available farmland, but represented 84% of all farms. Their study did not report on crop production, but their results implied that smallholders do not produce 70% global crops; it is unlikely they could produce this much food on 12% of available farmland, even if we assumed that small farms had higher yields and produced more food crops than larger farms. The second of these studies (Graeub) quantified the number and extent of family farms in the world and their production contributions. By using national family farm definitions, defining family farms based on farm size, or a combination thereof to represent regionally appropriate family farm definitions they estimated that ~98% of all farms globally are family farms, collectively managing 53% of all cropland, and meeting an estimated 36–114% of domestic caloric requirements for different countries. While Graeub's study highlighted the contribution of family farms, they also challenge the idea that all family farms are small farms. For example, farms in Brazil may be family owned but are large in size (while ~ 85% of farms in Brazil are family owned and cover ~ 25% of agricultural land, only 21% of farms are less than 2 ha in size and cover only 0.25% of the agricultural area). Together these two studies, quantified the global number of smallholders or family farmers, their cropping area, and detailed the differences between smallholders and family farms.

Two additional studies were recently published that tried to better estimate the proportion of food coming from smallholder farmers globally. Samberg estimated the contributions of smallholders in an analysis of 41 crops and 83 countries in smallholder dominant regions (Latin America, sub-Saharan Africa, and South and East Asia) that represent 35% of global cropland. They estimated that smallholders (which they defined as all administrative units with a "mean agricultural area" < 5 ha) produced 52.5% of food calories in their cross-regional sample. While, this study was a valuable step in mapping the geographic distribution of smallholders, using mean agricultural area within an administrative unit as an index of smallholder production is problematic because farm size distributions are highly skewed (e.g. Lowder). Following this, Herrero presented an analysis which modeled crop and livestock production, micro-nutrition production, and agricultural landscape diversity. Crop and animal data were related to farm size classes by combining crowd-sourced data on field sizes (Fritz et al., 2015) with national farm size distributions (Lowder) as a proxy for per pixel production by farm size. They reported that farms < 50 ha produce 56% of commodities and nutrients in their sample of 41 crops, 7 livestock, 14 aquaculture and fish products, across 161 countries. They also estimated that ~18% of food calories globally come from farms < 2 ha, and highlighted the valuable micronutrient contribution of smallholders, with farms < 20 ha producing ~ 70% of the world's vitamin A. While both Samberg and Herrero provided clear steps forward in understanding the role of smallholders in the food system, and in particular Herrero covering both animal and crop products, they did not use direct measurements of crop production and/or area by farm size, compute diversity calculations based on these direct calculations of production and/or area, or report on the broader role of smallholders in the food system (e.g. how much of their food is wasted and destined to non-food crops).

To fill these gaps, we compiled the first open source dataset to estimate crop production by farm size derived from actual farmer surveys containing crop-specific measurements of production or area that are cross-tabulated against each farm size class. Our dataset includes 154 crop types and covers 55 countries, which represents 51.1% of global agricultural area. We compare these direct estimates to those from the previous modeling studies (e.g., Herrero et al 2017; Samberg et al., 2016). In addition, we provide global estimates of the type of production (i.e., food, feed, processing, seed, waste, and other) across farm sizes and within each farm size class, to understand if more production from small farms is wasted from storage and transportation, and if this cancels the larger losses to biofuels and animal feed grown on large farms. Finally, we evaluate how the type of crops grown, crop species diversity, and macro-nutrient production varies by farm size. Our study is the first to directly evaluate the relationship between farm size, crop types, and crop diversity across a large range of farm sizes and geographic regions, and to assess how this diversity influences the amount of macro-nutrients available from crops. Together, these results provide the most comprehensive empirically grounded estimates of crop production by farm size currently available.

2. Methods

2.1. Data compilation

We compiled a global convenience sample of datasets that directly measured crop production and/or area by farm size for 55 countries at either the national, or subnational level (for a total of 3410 national or subnational units; see Fig. 1). These datasets were either agricultural census data or nationally (or sub-nationally) representative sample surveys, aggregated by administrative unit ($n = 34$ countries) or available at the micro-level (e.g., anonymized individual household level records) ($n = 21$ countries; of which 18 were household surveys and 3 were censuses that captured both family and non-family farms). The median year of the data was from 2013, with the oldest datasets from 2001 and the newest from 2015. The database has 154 crops which we matched with commodity names outlined in the Food and Agricultural Organization's (FAO) statistical database (2017) [FAOSTAT hereafter]. Where farm size and production were not cross-tabulated in the survey instrument (i.e. for 33 countries), we calculated production by farm size by first extracting either harvest area, cultivated area, crop area, or planted area to calculate farm size, and then converted area to production using FAOSTAT's national yield data. We tested the validity of this method, and found it to slightly underestimate production (full details of bias tests, inclusion criteria, variable descriptions, summary statistics, and per country statistics are given in the accompanying Data in Brief article). When farm size data was not available for a country, but we had micro-level data, we used the sum of farm plot areas for a given household as a proxy for farm size. Internal validation of the use of micro-data to fill in data gaps was not possible with our data, because we did not have both micro-data and farm size metrics for any of our countries, but we think the impact of using aggregate plot area is likely to be negligible for our results, as this was only used on 4.8% of administrative units in our dataset. Finally, all crop production data was tallied per country and validated against available national level reports, and to the FAOSTAT crop production database, both of which are computed from aggregated crop area estimates. In total, our dataset captures 51.1% of global crop production and 52.9% of global cropland area. We harmonized the datasets to match the WCA farm size categories: 0–1 ha, 1–2 ha, 2–5 ha, 5–10 ha, 10–20 ha, 20–50 ha, 50–100 ha, 100–200 ha, 200–500 ha, 500–1000 ha, and above 1000 ha. While we recognize that per country definitions of smallholders may not fall within these farm size bins, the majority of the datasets included reported these farm size breaks. We report our estimates by each WCA farm size class and cumulatively to allow flexible definitions of smallholders that are consistent with past attempts to quantify the relationship between farm size and crop production. Future researchers may use the accompanying, open-access dataset to redefine smallholders based on country specific definitions. Where European data included a > 100 ha category, we included this in the 100–200 ha range, making our classification less precise in > 100 ha groupings, in comparison to < 100 ha. Future researchers may wish to aggregate all 'large' farms into a > 100 ha bin for their specific needs, but here we present the results maintaining the disaggregation for surveys that reported it.

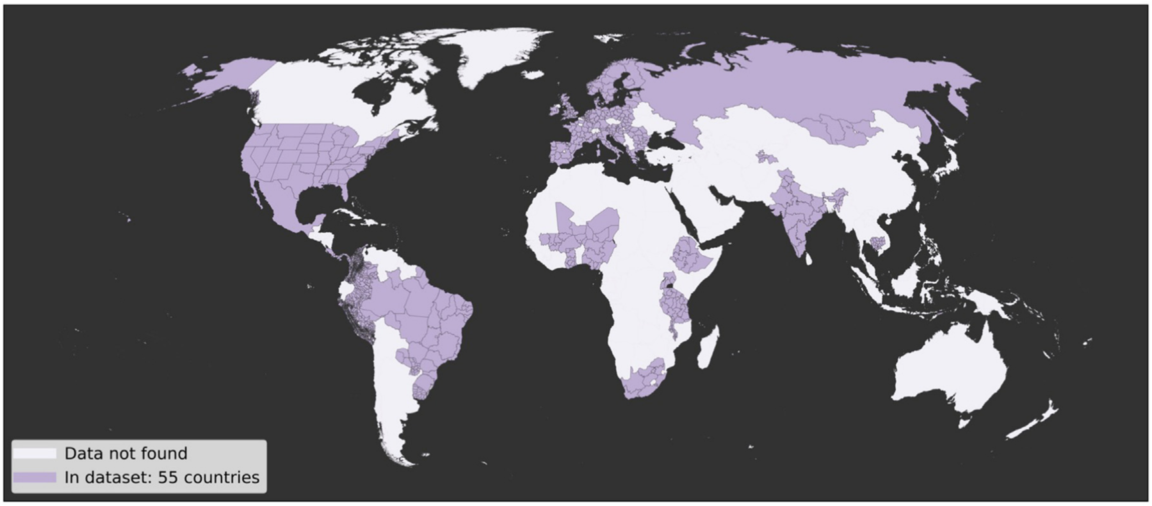

Fig. 1. Spatial coverage and resolution of our data on crop production by farm size. Countries shaded purple had directly measured data on crop production or harvested area.

2.2. Crop allocation

Following data compilation, we converted all tonnes of production to their kilocalorie (kcal/capita/day) equivalents using FAOSTAT conversion values per crop per country per year. We then applied the percent of feed, food, processing, seed, waste, or 'other' based on FAOSTAT's food balance sheets per crop per country per year. For example, in many countries maize can be used for human consumption, animal feed, a processed biofuel commodity, and seed, while some maize may be lost due to storage and transportation. FAOSTAT contains national totals for each of these types of crop allocation categories. We used these totals to calculate percentages per crop per country per year to allocate a certain portion of each crop's production towards food, feed, and the other crop allocation categories. While this approach does not account for the actual distribution of crop allocation by farm size, it is the most detailed information available and represents a proxy indicator based on what type and quantities of crops each farm size produces.

While certain FAOSTAT categories were straightforward to interpret and contained detailed definitions (e.g., 'feed' towards livestock and poultry and 'seed' set aside for sowing or planting), the processing category was ambiguous and required us to make assumptions. We followed Cassidy et al. (2013) and assumed that the reported oil crop processing category already separated out oil crop production for human consumption from that for industrial use, as well as protein dense cakes for animal feed. The waste category encompassed any loss of a given commodity during storage and transportation; losses incurred before and during harvest were excluded, as were losses due to household consumption. The 'other' category encompassed any uses not already accounted for.

After allocating all crop production to type of production (e.g., feed, food, other, etc.) in kcal/capita/day we evaluated how the global quantity of each varied across farm size classes. We also provide cumulative distributions of our estimates to encompass a sliding scale of definitions of small-farms (e.g., farms under 2 ha, farms under 50 ha, etc.), as may be required by different researchers and regional policy makers who might define 'small' using different thresholds. In addition to comparing how the type of production varies across farm sizes, we also analyzed how the types of production are distributed within each farm size class.

To obtain global estimates for the proportions presented in this manuscript, we computed 95% confidence intervals using the accelerated bias-corrected percentile limits bootstrap method (BCa), with 1000 iterations. BCa is useful extension of the basic percentile bootstrap, that decreases coverage error by accounting for bias in sample parameters (i.e., when the sample parameter — computed from the 55 countries — does not equal that of the average bootstrapped parameter, which in our case is our best estimate of global trends), and allowing the standard deviation of the bootstrap parameter to vary with the sample parameter (Manly, 2006). We chose to bootstrap all of the parameters of interest at the level of the country (n = 55), not the administrative unit (n = 3410), in an attempt to account for dependencies amongst administrative units in the same country and sampling campaign. Accuracy in uncertainty estimation for the global trends could be improved in future by adding to the number of countries in the dataset. While the BCa does not make any assumptions about the distribution of underlying random variable we use the natural log transform of production in our analysis for data visualization.

2.3. Crop species diversity and crop types

To estimate the relationship between crop diversity and farm size, we counted the proportion of unique number of species each farm size category produced within each administrative unit, and estimated the 95% CI's for each category using BCa. We note that different survey instruments have different crops included, and that farmer responses may not include the full diversity of crops that farmers actually produce. Thus, our estimates represent our current state of knowledge given empirical data, and are likely to be conservative. We present BCa estimates of crop diversity for each farm size using the administrative unit level to compare crop diversity distributions across farms within similar biogeographical landscapes (e.g., climate, soil, etc.). We also present BCa estimates of crop diversity while controlling for cumulative farm area, to give an indication of how diversity scales across the world in each farm size class. To do this we plotted cumulative numbers of unique species against cumulative area of administrative units for each farm size class, and estimated uncertainty for these curves by resampling the distribution of administrative units for each size class at random, a 1000 times (taking the 2.5th and 97.5th percentiles as lower and upper bounds, respectively).

To examine the variation in crop groups by farm size, we aggregated our crop species data into major commodity groups according to FAOSTAT definitions of cereals, fruit, oil crops, pulses, roots and tubers, tree nuts, vegetables, and other, and we estimated 95% CI's using BCa. Relying on the FAOSTAT classification has its limitations. For example, soy was classified as an oil crop, but it is also a pulse; therefore, this classification should be used as a guideline (see accompanying Data in Brief for crop grouping details). In order to examine whether different

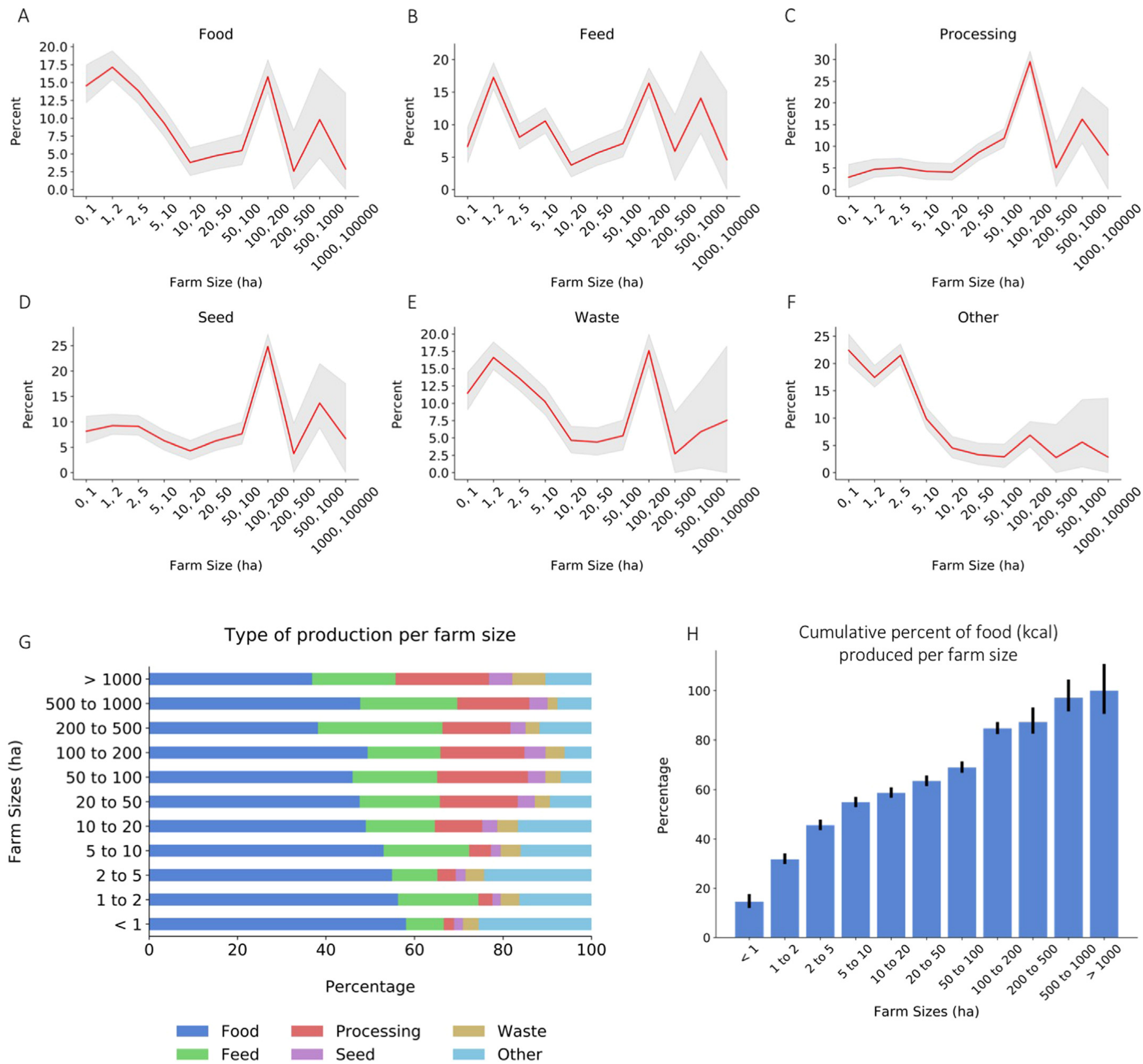

Fig. 2. A-F) Distribution of total global crop production (in kcal equivalents) across farm size groups different uses (e.g., food, feed, other, etc.). Grey shows bootstrapped 95% confidence intervals and red indicates the average. G) Allocation of use of production within each farm size class. H) Cumulative percent of global food production by farm size group with 95% confidence intervals. See Table S1 for underlying data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

farm sizes grew a different portfolio of crop groups, we used Sorensen's similarity index (Chao et al., 2006):

$$CC_{ij} = \frac{2C_{ij}}{S_i + S_j}$$

$S_i + S_j$

where $C_{i,j}$ is the number of species two farm size classes have in common, S is the total number of species found in the given farm size class, and i and j are the two farm size classes being compared; a score of 1.0 would represent perfect overlap in the crop groups grown between the two farm size classes.

2.4. Macro-nutrient production

We converted production of each crop in our dataset to its macro-nutrient (i.e., carbohydrate, protein, or fats in grams/capita) equivalent using FAOSTAT food balance sheets, and conversion factors per crop per country for the year matching the farm size data survey year. Any temporal data gaps in FAOSTAT were linearly interpolated per crop and country. As with production, we analyzed how macro-nutrient production varied both across farm-size classes and within farm-size classes and computed 95% CI's using BCa at the country level to estimate global figures.

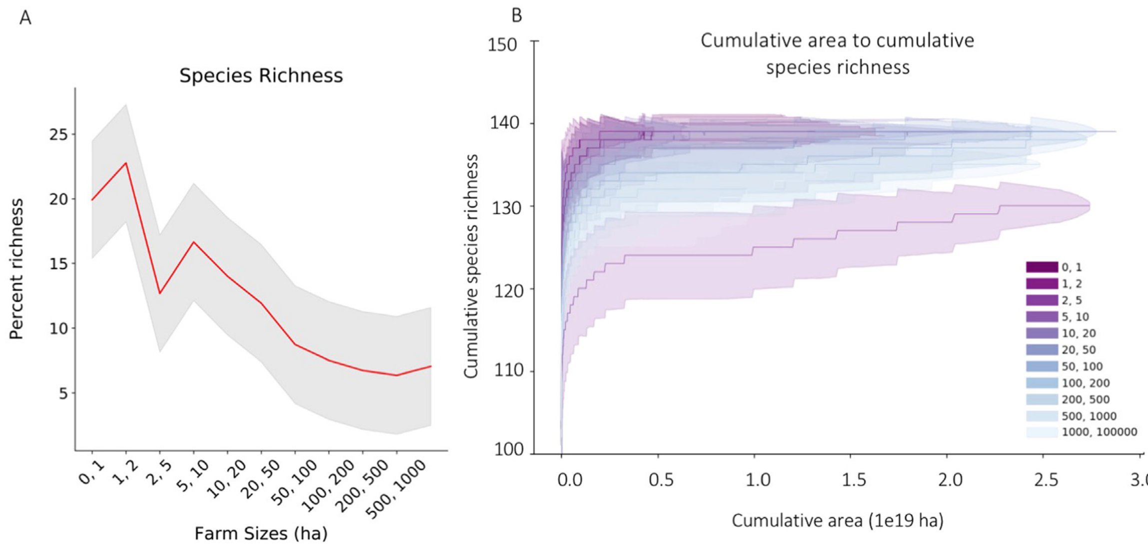

Fig. 3. A) Distribution of total species richness across farm size classes. Grey represents bootstrapped 95% confidence intervals; red is the bootstrapped average. The area of each administrative unit polygon weighted the data. See Table S2 for underlying data. B) Cumulative area to cumulative species richness curves. 1000 iterations generated the cumulative distributions between species richness and farm size. The starting point for cumulative distributions were randomly chosen each iteration. The lighter the colors, the larger the farm size classes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

3. Results

3.1. Crop allocation

The smallest two farm size classes (0–1 ha and 1–2 ha) are the greatest contributors to global food production compared to all other classes. Farms less than 2 ha produce 28–31% of total crop production and 30–34% of the global food supply (by calories; Fig. 2A-H) as extrapolated from the 55 countries in our dataset. Their contribution is slightly higher than their areal coverage of 24% of gross harvested area, suggesting small farmers have greater cropping intensity or higher yields than larger farms.

We found smallholders (farms < 2 ha) also allocate the largest percentage (55–59%) of their crop production to food compared to all other farm size classes (Fig. 2G). Generally, larger farms devote more of their production towards feed and processing. Farms between 200 and 500 ha have the largest allocation of their production to feed (16–29%) compared to farms < 2 ha who allocate 12–16% to feed. Farms > 1000 ha allocated 12–32% of their production to processing.

Farms < 2 ha contribute the most 28.1% (26–30%) to total food waste (on-farm and post-harvest loss) (Fig. 2E); however, this is mainly driven by this farm size group's large contribution to the total crop production. In our dataset, only 4% (2.3–6.1%) of smallholder production is wasted, compared to farms > 1000 ha that have the greatest amount of within farm size class waste at 7.5% (0.0–18.5%). However, the large uncertainty indicates both that there is substantial variation within large farms, and low confidence in the trend between farm size and waste holds at the global level. All farm sizes have fairly consistent allocations towards seed (means ranged from 2% to 5% with overlapping 95% CI's), while there is a trend that smaller farms allocate more to the ‘other’ category.

3.2. Crop species diversity and crop types

We found that species richness declined with increasing farm size (Fig. 3A). Diversity also scaled differently with area within different farm size classes, with greater turnover in unique species in small farms than in land allocated to larger farms (Fig. 3B).

Between farm size dissimilarity in species shows that larger farms, while harboring less diversity, and lower turnover in crop diversity across space, show greater specialization in certain crop groups than other farm sizes. Farms < 5 ha grow similar crops as each other (Sorensen's coefficient of 0.94), and farms > 100 ha have a perfect overlap in crops grown (Sorensen's coefficient of 1.0; Fig. 4). But farms greater than 20 ha grow a different array of crops compared to farms smaller than 20 ha (Sorensen's coefficient of 0.4–0.67) and farms greater than 100 ha have the lowest overlap with other farm size classes.

The crop portfolio of each farm size class shows that smaller farms (< 2 ha) produce a greater share of the world's fruits, pulses, and roots and tubers, while medium sized farms produce more vegetables and nuts, and large farms produce more oil crops and 'other' (Fig. 5). While all farm sizes contribute a large proportion to cereals, smaller farms devote a greater percentage of their overall production to cereals compared to other farm size classes.

3.3. Macro-nutrient production

The trends in macro-nutrient (carbohydrates, proteins, and fats) production across farm sizes follows that of the food production. Yet, of their own production, smaller farms produce a slightly higher percentage of carbohydrates (~ 0.08% more than the largest farm size class) while larger farms grow a slightly higher percentage of proteins (~ 0.05% more than the smallest farm size class). But these differences are minute, and considering the uncertainty estimates, there are no significant differences in the percentage of macro-nutrients produced within each farm size class (Fig. 6).

4. Discussion

4.1. Comparison to previous studies

Our dataset is the first global sample of direct crop-specific measurements of production or area by farm size. We found that farms < 2 ha produce 28–31% of total crop production and 30–34% of the food supply on 24% of gross agricultural land when using our directly measured farm size dataset. While our dataset covers 55 countries, with distinct datagaps in smallholder dominant Southeast and East Asia, our findings are in line with Samberg and Herrero's global estimates. This suggests that these three studies, using different methodologies, agree

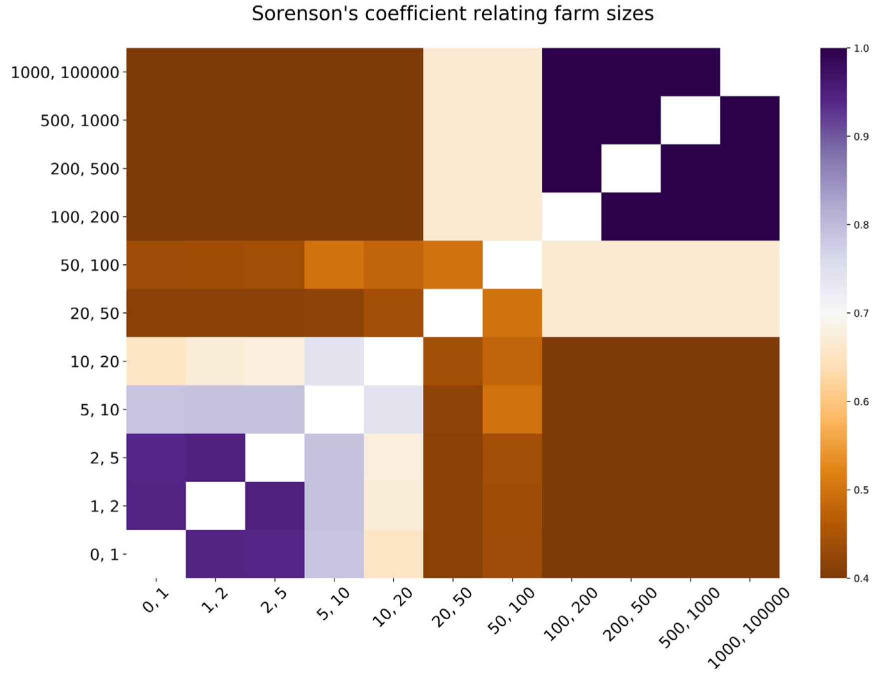

Fig. 4. Heat-map of Sorensen's coefficient between each farm size class pair. Purple indicates a greater similarity of crops grown between pairs of farm size classes, while brown indicates greater dissimilarity between crops grown.

that the previous estimate of smallholders producing 70–80% of global food production needs to be revised.

While our results are similar to the previous two modeling studies that estimated global smallholder production, there are several key differences. Our results offer more refined estimates using direct measurements of production by farm size instead of relying on modeling, includes a larger range of crop species than previously assessed, and our accompanying open-access dataset allows individual countries to have a reliable SDG baseline for how much of their food production is grown by smallholders (according to their own regional definitions of farm size). Samberg reported that farms < 5 ha produced 55% of global food calories, which is slightly larger than our equivalent estimate of 44–48% (Table 1, Samberg A.). To arrive at this estimate, they divided the total calories produced in each farm size category in their 83-country sample by total global calories produced by all countries. Their estimate could be considered a global estimate if one assumes that their sample of smallholder dominant regions account for most of the world's small farms (and their purposeful sample might suggest that interpretation). An alternative interpretation (which is similar to ours) is that the 83 countries in their sample are globally representative; in that case one would divide the calories produced by each farm size class by the total calories produced in those 83 countries. By this estimate, farms < 5 ha produced 76% of global food calories (Table 1, Samberg B.). The differences between Samberg and our dataset may be due to the countries and crops sampled and that Samberg relying on modeled results instead of direct measurements. Samberg used 41 crop species (while we included 154), and they use mean agricultural area instead of farm size distributions to understand crop production in smallholder dominant areas rather than crop production by farm size. Both Samberg and our study relied on household sample surveys to varying degrees (Samberg relied primarily on household surveys, while our dataset relied on them for 22.5% of total crop production). Household sample surveys systematically do not sample non-family farms and hence may be presumed to over-represent smaller farms when compared to agricultural censuses that survey all farm types. However, in our accompanying Data in Brief article we show that using household surveys to estimate national production is not significantly different than using FAOSTAT's national production estimates.

Our estimates were also close to Herrero's global estimates. < 50 ha. We found that farms < 2 ha produce 30-34% of the worlds food and < 50 ha produce 62–66% of the world's food, which is near Herrero's estimate of 18% and 56%, respectively (as in Herrero et al. (2017) Table 3). Our two studies capture different aspects of the global food system. Herrero incorporated livestock and fisheries, which are important source of nutrients and income for smallholders, while we only focus on crop production; our focus was due to data constraints and definitional mismatches between using farm size versus herd size, fishing area, or common pasture land. There are also crop species differences between the datasets, where Herrero used 41 crop species while we used 154. One key analytical difference is that Herrero's modeled results used field size as a proxy for farm size instead of actual reported farm size; we used field size as a proxy for farm size for only 4.8% of our data and direct measurements of production by farm size instead of modeled estimates. We found that using field size as a farm size proxy measure may slightly over estimate small-farms' production since it does not account for non-field elements of a farm (see the accompanying Data in Brief article). Additionally, Herrero disaggregated production to the pixel level based on field size, while Samberg disaggregated pixel-level production based on mean agricultural areas. Essentially, both methods assume a constant yield for each farm size class since they cannot directly link crop production with farm size. There is a widely observed inverse relationship between yield and farm size (IR), where smaller farms have higher yields (Bevis and Barrett, 2016; Henderson, 2015; Sen, 1962). For 66.7% of our dataset we also needed to use constant yields since direct data on production by farm size was not always available (we did have harvest area per crop by farm size, and minimally used data on planted area, cropped area, plotted area). Our dataset allowed us to test for the bias introduced by constant yield methods, and provides the relationship which researchers may use to correct for it. In the accompanying Data in Brief article, we found a small effect size that using constant yields slightly underestimates small-farms' production. Hence, our numbers, Herrero's and Samberg's may all slightly underestimate smallholders' crop production owing to this assumption.

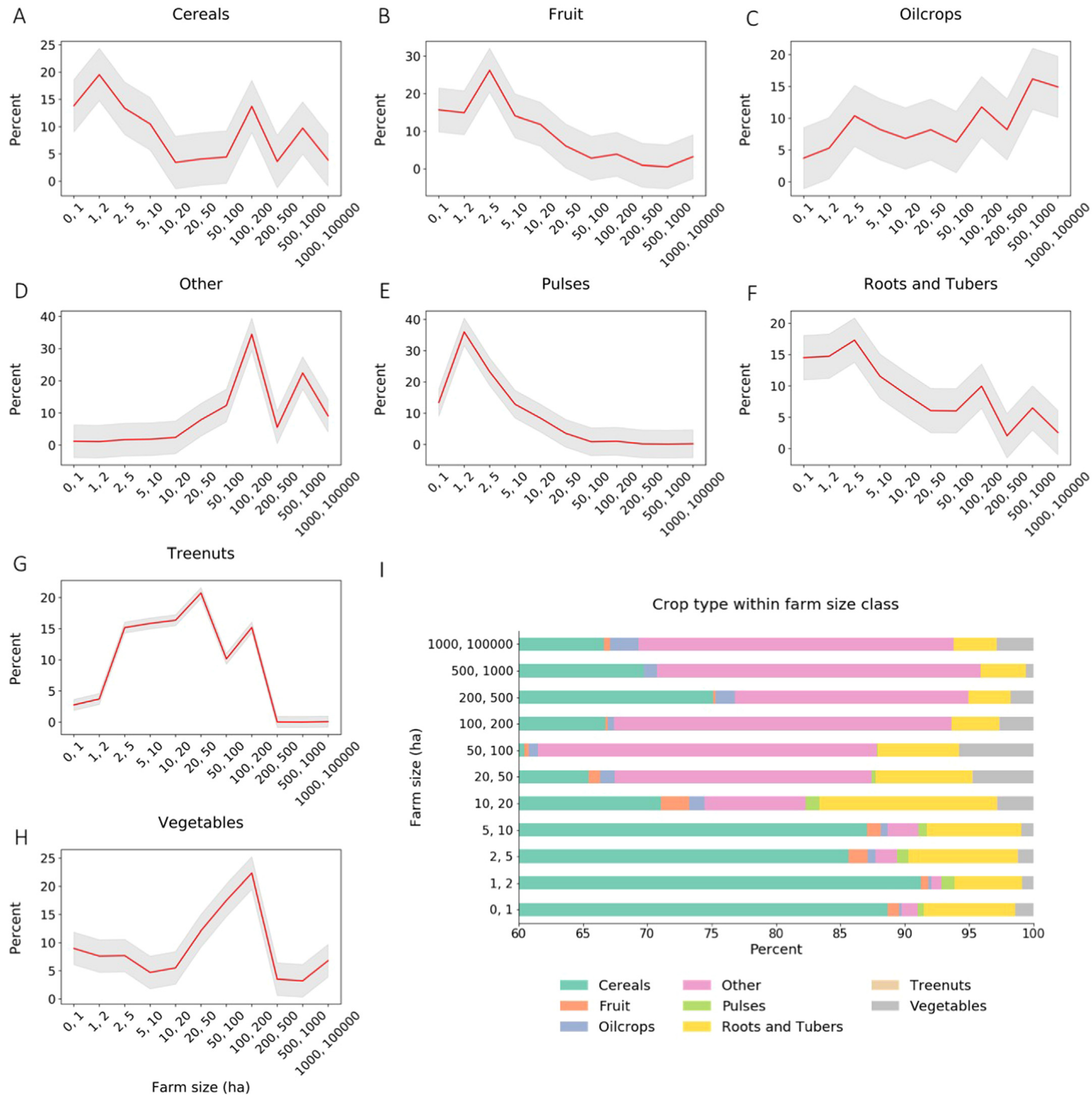

Fig. 5. A-H) Distribution of global production by crop type across farm size classes. Grey shows bootstrapped 95% confidence intervals and red is the average. I) Crop type portfolio within each farm size class. See Table S3 for underlying data.

4.2. Crop allocation

Our new findings on crop allocation across different farm sizes has important implications for food access and availability, as well as farmer livelihoods, since food, feed, processing, and seed market prices may differ from one another. We found nearly 60% of smallholder production is allocated to food. A smaller percentage is allocated towards feed (12–16%), which was surprising since smallholders often engage in mixed crop-animal farming systems (Smith et al., 2012); this finding may be explained by the fact that smallholders likely rely more on rearing animals that graze on pasture compared to largeholders.

Our results counter common thinking about smallholders' post-harvest loss, where improving cold storage and road infrastructure is a common development intervention to improve smallholder income by reducing wastage. Our dataset suggests that only a small percentage of smallholders' production is wasted. However, one reason for the low amount of smallholder waste in our results may be due to food allocated to the 'other' category. From our data, 19–23% of smallholder production went towards 'other' uses. This may be indicative of the need for smaller, farms to make use of all grown material in integrated farming systems (e.g., using rice stocks as a cover crop to promote soil health). Smallholders' large allocation towards 'other' may be indicative that waste reduction practices are common since smallholders are often resource poor and would achieve higher relative benefit

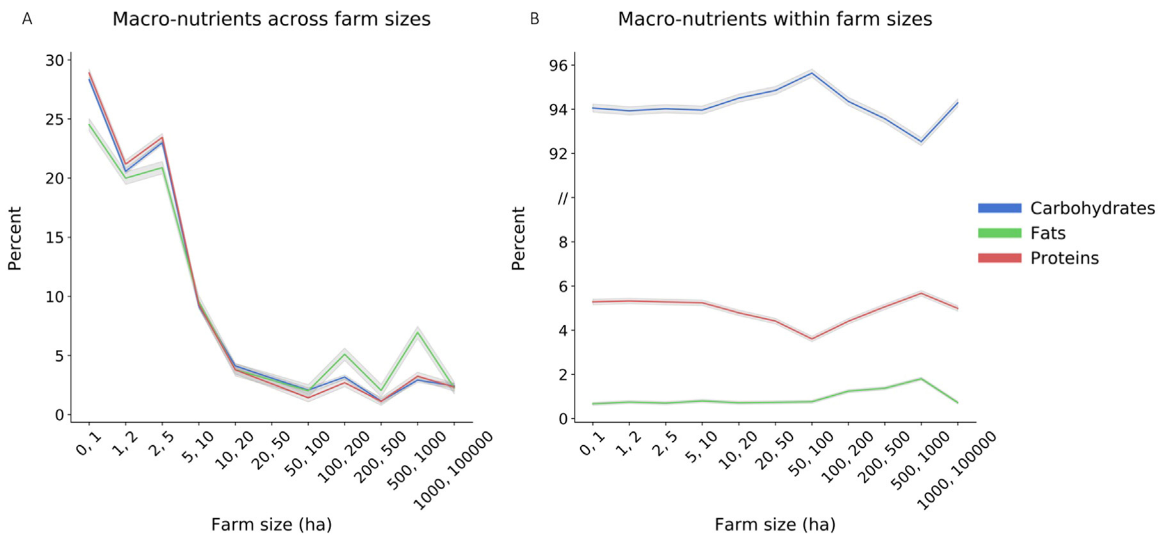

Fig. 6. A) Percentage of macro-nutrient production across farm size classes with 95% confidence intervals. B) Percentage macro-nutrient production within each farm size class with 95% confidence intervals. See Table S4 for underlying data.

Table 1
Comparison between global estimates for the percentage of food smallholders produce. For Samberg, A. uses estimates compared to global total food production, while B. compares estimates to total food production within their 83 sampled countries.

	< 2 ha	< 5 ha	< 50 ha	Methodological Distinctions
Our study	30–34%	44–48%	62–66%	Direct measurements 154 Crops 55 Countries
Herrero	18%	–	56%	Modeled estimates 41 Crops; 7 Livestock; 14 Aquatic Species Near global coverage
Samberg A.[a]	37%	55%	–	Modeled estimates 41 Crops
Samberg B.	52%	76%	92%	83 Countries Mean Agricultural Area as farm size proxy

[a] Note that we do not provide < 50 ha estimates for Samberg A because we cannot support the assumption that there are no farms < 50 ha outside of the 83 countries sampled by Samberg.

compared to largeholders to find a use for wasted crops.

While, interventions aimed to reduce smallholder post-harvest loss are still needed in many locales, there is also a need for agricultural researchers to identify why larger farms are wasting crops, because this group showed the greatest proportion of waste in any category (although this was country dependent, as shown by the wide bootstrapped confidence intervals). An estimated 1/4 of global food production from croplands is wasted from farm to market (Kummu et al., 2012). The waste data we used takes into consideration the quantities lost in the transformation of crop to processed goods (FAOSTAT, 2017). Hence, one possible reason for the increased wastage of larger farms' is that large farms on a whole engage in more crop production allocated for processing. Since FAOSTAT's definition of waste also encompassed waste incurred from poor distribution and storage, it was surprising that smaller farms did not have larger proportions of their crop wasted when the majority of smallholders are in countries with hot and humid climates and poorer storage infrastructure (Cohn et al., 2017). Future studies should disaggregate the types of crop production waste each farm size contributes to and local dependencies for these relationships.

4.3. Crop species diversity, crop types, and macro-nutrient production

Our data suggests a negative relationship between farm size and crop species richness. This adds significantly to the evidence on the literature's mixed finding on this relationship (Assunção and Braido, 2007; Rahman and Kazal, 2015; Van den Berg et al., 2007), as our study contains a wider range of farm sizes and more crop species than ever compared in previous studies. Due to the heterogeneity in data sources used to construct our dataset, there were not always a wide list of crop species included in each national survey, which may indicate a larger portion of primary crops were documented compared to local species. This limitation indicates that our findings are conservative and suggest that smaller farms, which are associated with producing many non-primary crops (Fifanou et al., 2011; Keleman et al., 2013), may have even higher degrees of crop diversity than we found.

There are several food access, nutrition, and climate resilience implications of higher crop diversity in smallholder systems. Since smallholders may be tied to subsistence-surplus production models and constrained to highly localized rural markets, their food access is often more reliant on their local communities' crop production compared to large farms (Baiphethi and Jacobs, 2009). The differences in types of crops produced by different farm sizes, and macro-nutrient contents that follow overall food production trends, supports the differences in micro-nutrient and macronutrient production across farm sizes, as found in Herrero. However, there are discrepancies. While smallholders produce a large amount of the world's protein rich pulses, we did not find that they produced a greater relative percentage of proteins than larger farms (i.e., all farm sizes allocated a similar percentage of their production to proteins). This suggests potential benefits from the promotion of mixed animal-crop systems for smallholders to access protein of which they are often deficient (Smith et al., 2012).

Our results suggest a nuanced view of the benefits of landscapes harboring different farm sizes, beyond the basic relationship between farm size and crop species richness. More diversified farming landscapes may need to include smaller farms because they collectively grow a higher diversity of crops than large farms, but also include larger farms because of their unique crop composition. Each farm size produces a greater quantity of certain types of crops than other farm sizes: smaller farms produce more fruits, pulses, and roots and tubers, while medium sized farms produce more treenuts and vegetables, and larger farms produce more oil crops. Promoting a diversity of farm sizes may encourage a greater diversity of crop types at the landscape level that can better provide more balanced diets and non-food needs, while potentially mitigating climate risks to the food system as a whole.

5. Conclusion

This study attempted to provide a global baseline for international policy measures aimed to support smallholder agriculture. These include a need for improved monitoring of SDG Goal 2.3, which aims to double food production of smallholders and increase nutrient availability; yet, Goal 2.3's monitoring framework does not use crop production by farm size as a national indicator (Sustainable Development Solutions Network (SDSN), 2015). Our findings suggest that previous estimates of the percentage of food produced by smallholders were either overinflated by public-sector opinions (ETC, 2009; Maass Wolfenson, 2013; FAO, 2014) or still needed directly measured data to assess quality (Herrero et al., 2017; Samberg et al., 2016), and that a nutrient diverse farming landscape would include a diversity of farm sizes, since each farm size produces a unique crop portfolio.

Critically, while our dataset is the first to use directly measured crop specific data on production or area by farm size, we were only able to find 55 countries with the necessary data to do this analysis. To monitor SDG Goal 2.3, there needs to be increased effort to build on datasets like ours through leveraging stakeholder networks. Ongoing efforts to use and add to our dataset will enable continuous food system monitoring over time with more geographic precision. We urge researchers and food system advocates towards data-driven policy monitoring to accurately assess the scale and progress of policy interventions.

Declarations of interest

None.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.gfs.2018.05.002.

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