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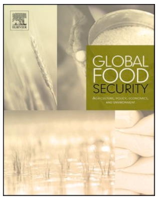

Nutrient production, water consumption, and stresses of large-scale versus small-scale agriculture: A global comparative analysis based on a gridded crop model

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ABSTRACT

Agricultural water consumption is the main contributor to water scarcity worldwide, while small-scale and large-scale agriculture have distinguishing characteristics. Significant gaps remain in the process-based agricultural production and water consumption estimates distinguishing small-scale and large-scale agriculture, which inhibits our deep understanding of where, how, and by whom crops are produced and against what water outcomes. We close this gap by leveraging a gridded crop model, covering 61% of the global harvested area using a 2010 baseline. Results show small-scale agriculture accounts for 43% of the total harvested area, however, contributes to relatively less nutrient production despite cultivating more food crops (relative to their total harvested area) than large-scale agriculture. This result challenges the assumption made by existing global scale studies when allocating national agricultural production to small-scale and large-scale agriculture, which (partly) ignores the differences in climate conditions, soil characteristics, input level, and type of irrigation that small-scale versus large-scale agriculture may have. The lower contribution is due to both water and soil fertility stress. Small-scale agriculture overrepresents in water-scarce regions but consumes much less blue water (38%) compared to its harvested area (54%). In water-scarce regions, soil fertility stress causes small-scale agriculture the unproductive green water utilization and a 70–90% unmet crop production potential. Our findings demonstrate the unequal exposure and contribution to water scarcity between small-scale and large-scale agriculture and between food and non-food crops. Understanding such disparities is one of the first and necessary steps toward enhancing the resilience and sustainability of agricultural systems.

1. Introduction

Globally, there are over 600 million farms, which consist of one or more plots (FAO, 2023; Lowder et al., 2021). These farms differ substantially in what crops they cultivate, farm management, and size (FAO, 2014; Giller et al., 2022; Rapsomanikis, 2015). Understanding where, how, and by whom crops are produced is crucial for addressing food security. Small-scale and large-scale farms (agriculture) are generally differentiated in this context based on farm size, economic size, and farming system (FAO, 2019). Generally, while large-scale farms account for a large quantity of global food production, the majority of farms are small-scale (Herrero et al., 2017; Ricciardi et al., 2018). These small-scale farms are crucial for sustaining livelihoods, food security, and economies in rural areas (Frelat et al., 2016; Giller et al., 2022; Tittonell and Giller, 2013), but many are characterized by persistent productivity gaps that drive poverty and food insecurity (Fan and Rue, 2020; FAO, 2014; Tittonell and Giller, 2013).

Agricultural production is linked closely to water scarcity. On the

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one hand, agriculture is the primary consumer of both blue (surface water and groundwater) and green (direct use of precipitation) water resources (unknown FAO, 2021; Hoekstra and Mekonnen, 2012). Here, water consumption refers to the part of water use that is not returned to the environment within the same hydrological basin (Hoekstra et al., 2011). The Sustainable Development Goals (SDGs) aim to end poverty and achieve food security for all by 2030, including a doubling of both the agricultural productivity and income of small-scale farmers (IAEG-SDGs, 2020; UNGA, 2015). Meeting these targets will inevitably affect other SDG domains, particularly water (SDG 6). On the other hand, water scarcity stalls or limits production on about 39% of global cropland, and about 70% of irrigated croplands (IIASA FAO, 2021; Liu et al., 2022; Pörtner et al., 2022). These impacts will likely be exacerbated by climate change (Liu et al., 2022).

The context of small-scale and large-scale agriculture has not been sufficiently addressed in the global studies on water for agricultural production. Recent advances in water consumption have not explicitly considered farm size in the estimates (Chiarelli et al., 2020; Mialyk et al., 2024; Tamea et al., 2021; Tuninetti et al., 2020). Significant gaps remain in how much water small-scale and large-scale agriculture consume for what kind of agricultural production. Existing analysis indicates that more than 70% of small-scale agriculture from some countries is located in water-scarce regions (Pörtner et al., 2022; Ricciardi et al., 2020). Small-scale agriculture may also have a lower irrigation coverage in water-scarce regions (Ricciardi et al., 2020; Su et al., 2022). Lower irrigation coverage does not equal to water consumption, which links directly to water scarcity, because water consumption varies a lot among crops due to the differences in natural environment and input levels.

Existing methods used to estimate the production of small-scale and large-scale agriculture at the global level also face a great barrier to be extended to water consumption analysis, which requires a more process-based method. For example, Herrero et al. (2017) estimated the farm-size-specific agricultural production by allocating the national production to each farm size according to the length of growing period, which is based on the rainfall regime, i.e., precipitation and reference evapotranspiration. As acknowledged in their paper, this allocation is not based on the actual spatially explicit distribution of small-scale and large-scale agriculture, which is yet to be developed. Besides rainfall regime, all other factors were assumed the same for all farm sizes. Ricciardi et al. (2018) advance the farm-size-specific agricultural production estimate by collecting farm-size data from the agricultural census at the national or subnational level. Their study reflects the actual farm size distribution at the regional level. However, among the 55 countries covered by their study, the same yield was assumed for both large-scale and small-scale agriculture for 33 countries due to data availability regardless of the different natural production environments and input levels they might have. A few studies estimate the agricultural production of small-scale agriculture by overlapping the grid-level farm size distribution and agricultural production, which assumes the same yield for both small-scale and large-scale agriculture if they belong to the same grid cell (Nozaki et al., 2023; Samberg et al., 2016). Again, even within the same grid cell, input level and irrigation could be different. A lack of process-based production estimates not only brings significant uncertainties to current farm-size-related discussions but also inhibits water consumption estimates, which depend on, to name a few, the type of crops, climate conditions, soil characteristics, input levels, and type of irrigation.

To close the gap in process-based agricultural production and water consumption estimate and guide efforts to address global food and water insecurity, we leverage a recently developed global gridded crop model to estimate the crop production and water consumption of small-scale and large-scale agriculture across water-scarce and water-abundant regions. Our analysis covers 61% of the global cropland in 55 countries, representative of the year 2010, and distinguishes small-scale from large-scale agriculture based on farm size and production value size. Using a global crop model (ACEA, AquaCrop-Earth@lternatives (Mialyk et al., 2021; Mialyk and Su, 2024)) and geospatial datasets on climate, soil characteristics, crop types, farm sizes, input levels, and type of water supply (FAO and IIASA, 2021; Fischer et al., 2021; Mialyk et al., 2024; Su et al., 2022), we evaluate how small-scale and large-scale agriculture consume water and are differentially affected by water stress (a lack of irrigation facilities) and soil fertility stress.

2. Methods

We estimate the geographic distribution of small-scale and large-scale agriculture across water-scarce and water-abundant regions, their blue and green water consumption, and the water stress (a lack of irrigation facilities) and soil fertility stress on crop production. In this section, we first describe how we defined small-scale and large-scale agriculture in 55 countries using multiple global datasets, then, we discuss how we classified water-scarce and water-abundant regions, followed by how we used a crop model to estimate water consumption and yield. We also explain how we implemented additional irrigation and fertilization scenarios to analyze the stresses of water and soil fertility on crop production. Finally, we introduce the crop nutritional value to aggregate crop production for stress analysis.

2.1. Geographic distribution of small-scale and large-scale agriculture

We limit ourselves to small-scale and large-scale agriculture for crop production. We divided the harvested area of farms into small-scale agriculture if it meets one of the three criteria: (1) the farm with size under 2 ha (Lowder et al., 2021), (2) farms belonging to subsistence farming system (Morton, 2007), and (3) smallest farms that accounted for ≤40% of national cropland and that accounted for ≤40% of national agricultural revenue (here, crop production value as an approximate) at the same time (SDG definition) (FAO, 2019). The remaining harvested area was classified as large-scale agriculture. One exception is fodder crops which are only based on farm size because of data availability. One of the main input datasets for small-scale and large-scale agriculture classification is the best available crop-specific and farm-size-specific harvested area at 5-arcmin spatial resolution per crop, per farm size, and per farming system for the year 2010 across 55 countries (half of the global harvested area) (Su et al., 2022). SI Appendix, S1 lists all 55 countries; SI Appendix, S3 illustrates how the three criteria were implemented and lists the datasets used to classify farms in each country. This resulted in a 5-arcmin map of crop-specific harvested areas for small-scale and large-scale agriculture per (high-input) irrigated, high-input rainfed, low-input rainfed, and subsistence farming systems, where the farming systems were defined by SPAM2010 (Yu et al., 2020).

2.2. Water scarcity dataset and climate classification

In this study, water scarcity refers to blue water scarcity. Water-scarce regions were retrieved from an annual water scarcity index database at 30-arcmin spatial resolution for the year around 2000 (Mekonnen and Hoekstra, 2016). In this dataset, the water scarcity index was calculated as the ratio of water consumption to water availability. Water availability is the volume of surface water and groundwater (blue water) from local runoff and upstream inflows after subtracting the environmental flow demands. Water consumption is the blue water consumed by all the sectors, including agriculture, livestock, industries, and domestic. The water scarcity index was calculated at the monthly scale and averaged to get the annual value. We classified the 30-arcmin grid cell as water-scarce if its annual water scarcity index is larger than 1, meaning water consumption exceeds water availability, otherwise as water-abundant. We overlapped the resulting water scarcity classification with the above geographic distribution of small-scale and large-scale agriculture to add the water scarcity dimension. There might be some inconsistencies in crop water consumption between our results and the water scarcity index database, but we do not expect these inconsistencies to change water scarcity classification to a large extent (see uncertainty discussion). We also used climate classification from GAEZv4 (FAO and IIASA, 2021; Fischer et al., 2021) for overlapping analysis with the geographic distribution of small-scale and large-scale agriculture, where the climate is classified as 13 types based on 2-character Köppen–Geiger climate classification.

2.3. Crop production and (blue and green) water consumption estimations

Crop production and (blue and green) water consumption of crops was estimated by a global gridded crop model, ACEA (AquaCrop-Earth@lternatives) (Mialyk et al., 2021; Mialyk and Su, 2024). ACEA was developed based on AquaCrop-OSpy (Foster et al., 2017; Kelly and Foster, 2021), which is a water-driven crop growth model built based on key concepts from the FAO AquaCrop model (Steduto et al., 2012; Vanuytrecht et al., 2014). It describes crop growth (canopy cover development), crop transpiration, soil evaporation, and blue (irrigated water from surface water and groundwater and capillary rise of groundwater) and green (direct use of precipitation) water consumption at a daily step. ACEA is one of the crop models contributing to the model comparisons of the ISIMIP 3a round (The Inter-Sectoral Impact Model Intercomparison Project) (ISIMIP, 2023) and GGCMI (Global Gridded Crop Model Intercomparison) (Franke et al., 2020).

The crop model was set up to simulate small-scale and large-scale agriculture based on farming systems at a 30-arcmin spatial resolution from 2006 to 2012 on a daily step. We assume that the irrigated farming system is always high-input and that the main difference between low-input (and subsistence) rainfed and high-input rainfed farming systems is the level of soil fertility stress, determined by whether fertilizer is applied or not within the crop model. This assumption is supported by the evidence that climate, water, and soil fertility stress explain 60%–80% of global yield variability (Cecil et al., 2023; Mueller et al., 2012; Ray et al., 2015). Note, subsistence farming was aggregated into low-input farming system during simulations. In addition to farming systems, the presence of groundwater and type of irrigation (surface irrigation, sprinkler irrigation, drip irrigation, and flooded (only for rice)) were considered per grid cell as well. To enable soil fertility simulation in ACEA, we added the soil fertility module to ACEA based on the FAO AquaCrop reference manual, which adjusts the maximum canopy cover, canopy expansion, canopy decline, and biomass water productivity according to the soil fertility stress (Steduto et al., 2012; Vanuytrecht et al., 2014) (SI Appendix, S4.1).

Input data includes climate, CO_2 concentration, groundwater level, soil composition, soil fertility stress, crop calendar, crop parameters, crop distribution, and irrigation types. Depending on the details of available crop parameters, simulated 171 crops were divided into three tiers. Tier 1 includes 39 crops, covering 79% of the total harvested area. We used individual crop-specific parameters for each tier 1 crop from Mialyk et al. (2024); Mialyk and Su (2024), which were originally from the AquaCrop manual and the literature. In addition, we use localized maximum canopy cover and harvest index for low-input and high-input (and irrigated) farming systems separately based on the GAEZv4 database (FAO and IIASA, 2021; Fischer et al., 2021). Tier 2 includes 16 crops plus two additional generalized crops, covering 3% of the harvested area. For tier 2 crops, we still use individual crop-specific parameters for each crop but without localized maximum canopy cover and harvest index because of data availability issues. Tier 3 includes 116 crops, covering 18% of the harvested area, most of which are fodder crops. For tier 3 crops, we use the crop parameters of a similar crop from tier 1 and tier 2 because of a lack of specific data. The choice of similar crops was taken from Mialyk et al. (2024) who considered the similarity in biological classification, growing area, and crop calendar. Note that for tier 1 and tier 2 crops, all the crop phenology parameters (e.g., time to emergence, maturity, senescence, canopy growth, and decline coefficient) are also location-specific. The soil fertility module needs calibration for all tier 1 and tier 2 crops. The calibrations require local crop-specific maximum canopy cover and potential biomass production for both low-input and high-input farming systems, which were retrieved from GAEZv4. GAEZv4 provides Leaf Area Index (LAI) instead of Canopy Cover (CC), thus we collected crop-specific LAI-CC relationships from literature to translate GAEZv4 data. The 171 crops by tiers, calibration of the soil fertility stress module, and all the input data and parameters are explained in detail in SI Appendix, S4.2 and S4.3.

During postprocessing, the simulated yield was scaled to FAO yield to accommodate all other impacts from weeds, diseases, as well as regional cultivars, and field management because of a lack of data. The ACEA outputs were compared against a global dataset of historical yields for major crops (GDHY) (Iizumi and Sakai, 2020), datasets of downscaled FAOSTAT yield from GAEZv4 and SPAM2010, and water consumption from the global crop models LPJmL (Bondeau et al., 2007), PEPIC (Liu et al., 2016), EPIC-IIASA (Balkovič et al., 2013), and pDSSAT (Elliott et al., 2014b) under historical scenarios for ISIMIP 3a round. These comparisons (technical validation) show good overall consistency of our estimations with other global datasets (SI Appendix, S5).

In the end, the 5-year average of yield and water consumption from ACEA at 30 arcmin were matched to 5-arcmin distribution of small-scale and large-scale agriculture according to the farming system and types of water supply. Here, we assume there is no difference between small-scale and large-scale agriculture if they are in the same grid cell, plant the same crops, and belong to the same farming system. SI Appendix, S4.4 explains model simulations and postprocessing in more detail.

2.4. Analysis of blue water stress and soil fertility stress

We conducted a scenario analysis to estimate the (blue) water stress due to no irrigation facilities and soil fertility stress on small-scale and large-scale agricultural crop production. For water stress, we implemented a scenario with additional irrigation (sprinklers) for all rainfed farming systems. This means low-input and high-input rainfed crops were assumed to be irrigated where water stress occurs because of insufficient precipitation (green water), and all other parameters including soil fertility stress remain the same. For soil fertility stress, we implemented a scenario with additional fertilization for all low-input (or subsistence) rainfed farming systems, i.e., we applied the soil fertility stress of high-input farming system to low-input farming system, leaving all other factors including irrigation the same. To assess the interactions between water and soil fertility stress, we implemented a combined scenario with additional irrigation as well as fertilization to all rainfed farming systems where applicable.

2.5. Crop nutritional value for crop production aggregation and comparison

Where crop production is simulated in tons, one ton of rice is not the same as one ton of maize. One way to compare the production of different scenarios over crops is to translate crop production into nutrient production, e.g., energy and protein. The disadvantage of this translation is that we exclude non-food crops but at the same time, it helps us focus on the implications of crop production for food security, which is relevant to small-scale agriculture studies. Thus, we divided all 171 crops into 121 food crops and 50 non-food crops (SI Appendix, S4.3). Food crops include cereals, fruits, pulses, roots and tubers, vegetables, and some oil crops (e.g., groundnut and soybean). Non-food crops include fodder crops, sugar crops, fibre crops, stimulants, and some oil crops (e.g., sunflower). To estimate the nutrient production from crops that can be potentially consumed, crop nutritional value was compiled for 86 out of 121 food crops (73% of the total harvested area) from FAO/INFOODS (Vincent et al., 2020) and the U.S. Department of Agriculture (USDA, 2021). To capture the diversity within crop species, we averaged the nutritional value of different crop cultivars. Energy, Protein, Calcium, Zinc, Iron, Vitamin A, and Folate were selected as nutritional values to represent the different nutritional characteristics of the various crop groups and to reflect the importance of nutritional aspects in the food security discussion (Herrero et al., 2017). We only considered the edible proportion of the harvested crop; but when different parts of the crops are consumed (e.g., the leaves and roots of cassava), we added up the nutritional values supplied by all the different parts to calculate the total edible nutritional values that can be potentially harvested from these food crops.

3. Results

3.1. The crop production of small-scale and large-scale agriculture in water-scarce and water-abundant regions

Using the best and recently available global datasets, we were able to cover 55 countries in our study, which collectively represented 61% of the global crop harvested area in 2010 (for a list of all countries see SI Appendix, S1). Out of the total harvested area within the study area, 43% is classified as small-scale agriculture, which produces 34–50% of nutrients globally (Table 1, Fig. 1). However, their contribution to 6 out of 7 investigated nutrients is significantly less than 43% (the harvested area occupation), which is observed for water-scarce and water-abundant regions separately as well. This indicates a relatively low nutrient production per unit of land use of small-scale agriculture, which challenges the yield assumptions made by existing studies when allocating agricultural production to different farm sizes.

The majority of small-scale agriculture (68%) is located in water-scarce regions, especially in developing countries, and dry climate zones (Table 1, SI Appendix, S2). In contrast, less than half of large-scale agriculture (43%) is located in water-scarce regions—a substantially lower figure compared to small-scale agriculture (Fig. 2, Table 1). Although climate may partly explain part of it (more large-scale agriculture is located in fully humid regions) we observe that small-scale agriculture faces more water scarcity compared to large-scale agriculture even within the same climate zone (SI Appendix, S2). This illustrates the uneven distribution of water risk between small-scale and large-scale agriculture, which is the consequence of uneven natural and social resource distribution. Note that small-scale agriculture facing more water scarcity is observed particularly within countries where a middle range of harvested area (10–70%) faces water scarcity (SI Appendix, S2).

Table 1
Selected harvested area and water consumption characteristics of small-scale and large-scale agriculture. This table shows that most small-scale agriculture is in water-scarce regions, with more low-input farming systems, consuming less blue water, relying more on green water, and focusing more on food crops.

	Small-scale agriculture	Large-scale agriculture
Share in total harvested area	43%	57%
Percentage of harvested area in water-scarce regions	68%	43%
Water-scarce regions		
- Share in total harvested area	54%	46%
- Percentage of food crops	86%	71%
- Percentage of irrigated harvested area	18%	30%
- Percentage of low-input (or subsistence) rainfed harvested area	64%	28%
- Share in blue water consumption	38%	62%
- Share in green water consumption	55%	45%
- Percentage of green water in total water consumption	88%	79%
Water-abundant regions		
- Share in total harvested area	30%	70%
- Percentage of food crops	85%	61%
- Percentage of low-input (or subsistence) rainfed harvested area	40%	19%
- Share in blue water consumption	22%	78%
- Share in green water consumption	30%	70%
- Percentage of green water in total water consumption	98%	97%

Among food and non-food crops, food crops account for a higher share of area in small-scale agriculture while large-scale agriculture also produces a large share of non-food crops (Table 1, Fig. 2). For small-scale agriculture in water-scarce regions, cereals (54%), such as critical staples like rice, wheat, and maize, are the most common crops, followed by oil crops (14%) and pulses (12%). Importantly, cereals and pulses are predominantly food crops, which are often critical for regional, national, and even global food supply chains. As such, the geographic location of small-scale agriculture in primarily water-scarce regions is a potential risk factor for food security, especially in the context of increased volatility of water supply under climate change and expansion in non-agricultural water demands in many of these regions.

3.2. The unequal blue water consumption in water-scarce regions

Despite our finding that most small-scale agriculture is in water-scarce regions, only a small fraction of them currently irrigate their crops (18%). Here, irrigation refers to whether they are equipped with irrigation facilities. Irrigation is applied in small-scale agriculture across India, Mexico, Peru, South Africa, and Europe, but hardly ever applied in small-scale agriculture in Africa based on results from 55 countries. Contrarily, a larger proportion of the area under large-scale agriculture is irrigated in water-scarce regions including in Africa (30%) (Table 1). A lack of irrigation indicates that small-scale agriculture may have less ability to adapt to water scarcity, despite being more heavily co-located in water-scarce regions relative to large-scale agriculture.

As a result of the differences in types of crop, climate conditions, soil characteristics, and irrigation access and use, in water-scarce regions, small-scale agriculture consumes relatively less blue water compared to large-scale agriculture. Small-scale agriculture consumes only 38% of total blue water despite accounting for 54% of the harvested area in water-scarce regions (Table 1). The blue water consumed by small-scale agriculture in water-scarce regions is concentrated on cereals, sugar crops, and oil crops (Fig. 3). In contrast, the blue water consumption for large-scale agriculture is greater and applied to a more diverse set of crops, including cereals, sugar crops, oil crops, fodder crops, fibres, than small-scale agriculture (Fig. 3). On average, non-food crops consume more blue water (and total water) per hectare than food crops despite the large variance in unit water consumption among crops. This demonstrates an unequal blue water consumption in water-scarce areas between small-scale agriculture and large-scale agriculture and between food crops and non-food crops.

At the same time, small-scale agriculture relies more on green water for crop production, indicating its vulnerability and exposure to rainfall pattern change and droughts, and thus climate variability in the long term. Green water accounts for 88% of the total water consumption of small-scale agriculture in water-scarce regions, which is higher than large-scale agriculture (79%) (Table 1). Over 90% of the total water consumption is green when small-scale agriculture produces stimulants (e.g., cocoa, tea, and coffee), roots and tubers, fodder crops, pulses, oil crops, fruits, vegetables, and fibres. Since stimulants, oil crops, fruits, and vegetables are also critical income sources for small-scale agriculture, risks to these crops from climate variability must be carefully considered.

3.3. Water and soil fertility stress on the crop production of small-scale and large-scale agriculture

Both water and soil fertility stress hamper the crop production of small-scale and large-scale agriculture, but small-scale agriculture faces higher water and soil fertility stress, which can be inferred from scenario analysis (Table 2). The overall magnitude of soil fertility stress for small-scale agriculture is higher than the one experienced by large-scale agriculture. Because the low input (or subsistence) rainfed farming

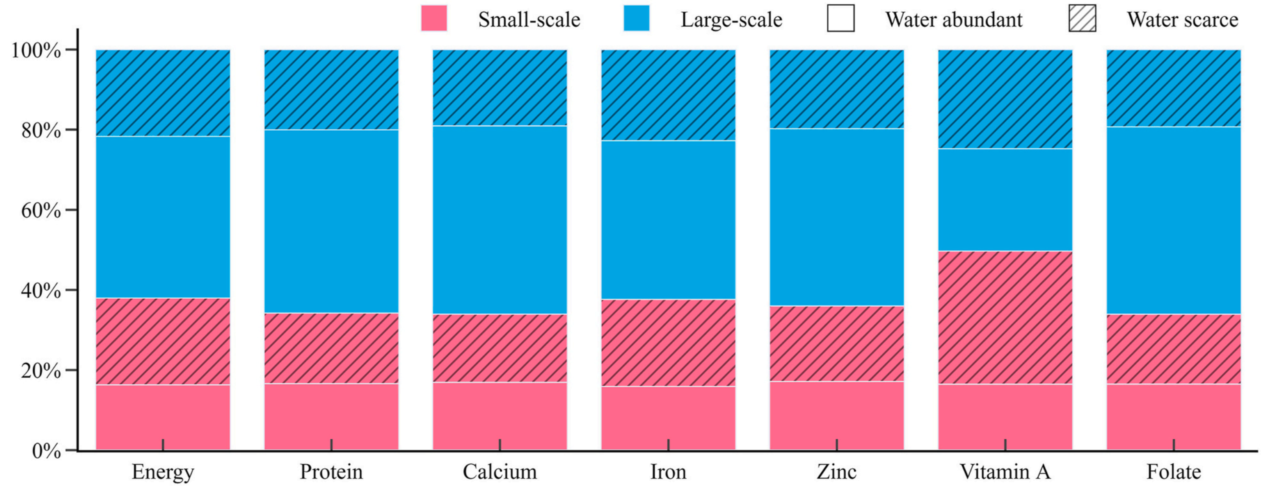

Fig. 1. The contribution to nutrient production by small-scale (red) and large-scale agriculture (blue) from water-abundant regions (no texture) and water-scarce regions (with '/' texture).

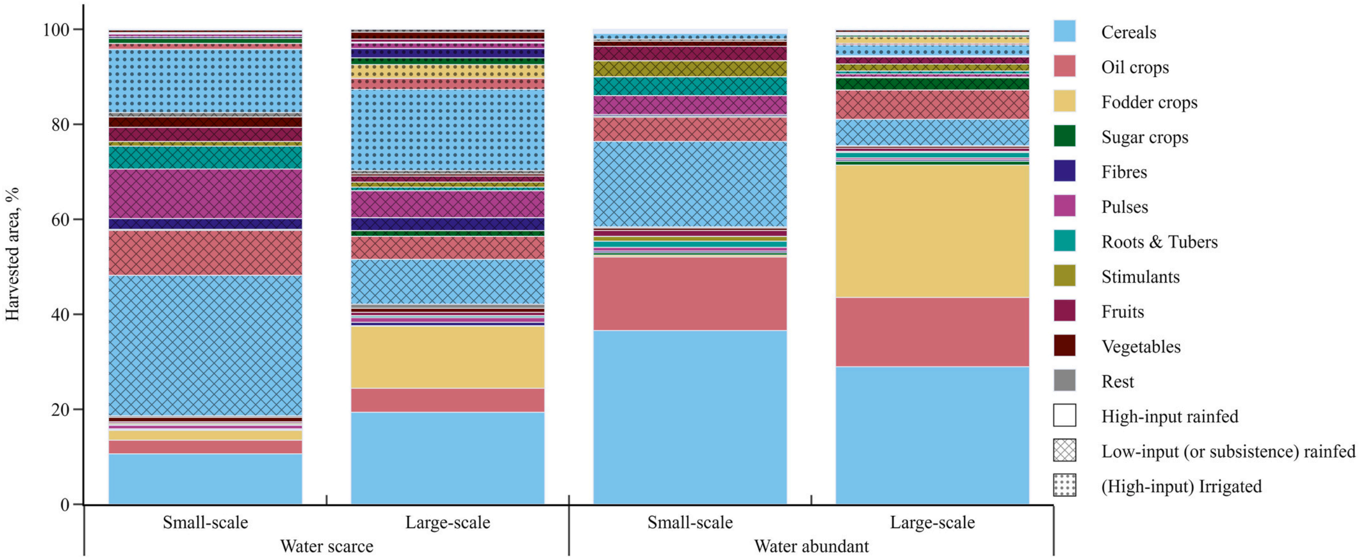

Fig. 2. Share of harvested area within water-abundant and water-scarce regions, for small-scale and large-scale agriculture, and combinations of crop groups (color), and farming systems (texture).

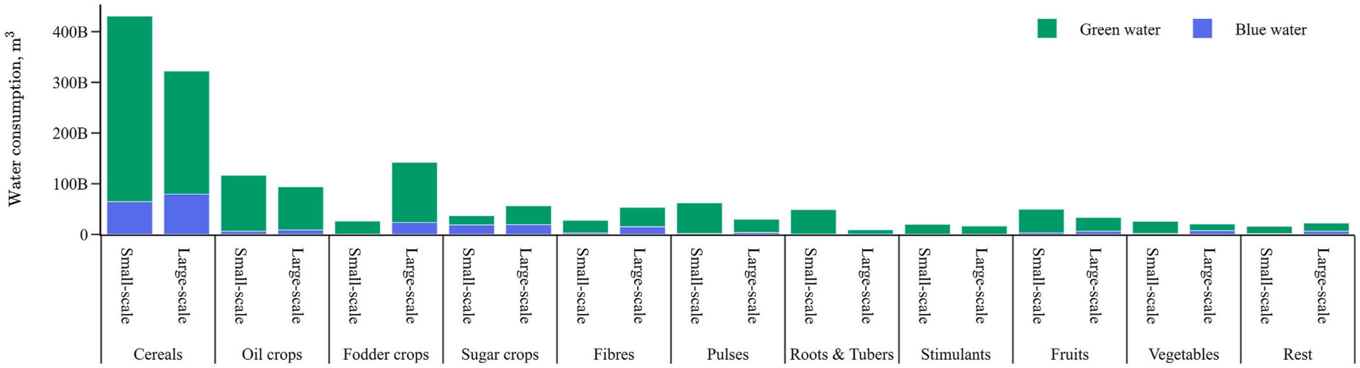

Fig. 3. Blue and green water consumed (m3) by small-scale and large-scale agriculture in water-scarce regions per crop group.

system is more common in small-scale agriculture (Table 1), insufficient crop growth may not benefit from only additional irrigation. Actually, 44% of small-scale agriculture is low-input farming system and faces water scarcity at the same time, which is much higher than large-scale agriculture (12%) (Table 1, Fig. 4). This is why, by relieving soil fertility stress, the production could increase by 70–90% for small-scale

Table 2

Changes of blue, green, and total water consumption and crop production (produced nutrition) compared to baseline under additional irrigation, fertilization, or both scenarios of small-scale and large-scale agriculture in water-scarce regions and water-abundant regions.

Scenario	Item	All	Water-scarce		Water-abundant	
			Small-scale	Large-scale	Small-scale	Large-scale
Irrigation	Blue water	247%	285%	159%	980%	382%
	Green water	−4%	−5%	−3%	−4%	−4%
	Total water	21%	29%	31%	17%	9%
	Energy	20%	31%	35%	18%	6%
	Protein	19%	35%	35%	17%	6%
	Calcium	16%	31%	32%	15%	5%
	Iron	23%	35%	40%	21%	7%
	Zinc	18%	31%	34%	17%	6%
	Vitamin A	24%	35%	30%	15%	9%
	Folate	18%	41%	34%	12%	5%
Fertilization	Blue water	0%	0%	0%	1%	0%
	Green water	1%	1%	1%	0%	1%
	Total water	1%	1%	0%	0%	1%
	Energy	39%	78%	17%	46%	27%
	Protein	37%	70%	18%	40%	33%
	Calcium	46%	84%	22%	50%	40%
	Iron	40%	84%	20%	43%	27%
	Zinc	42%	85%	18%	49%	32%
	Vitamin A	54%	80%	20%	86%	33%
	Folate	48%	90%	26%	49%	41%
Irrigation and Fertilization	Blue water	262%	312%	165%	1024%	402%
	Green water	−4%	−5%	−3%	−4%	−3%
	Total water	23%	33%	33%	18%	10%
	Energy	73%	150%	65%	74%	35%
	Protein	68%	147%	66%	64%	39%
	Calcium	74%	155%	67%	74%	47%
	Iron	79%	168%	75%	73%	35%
	Zinc	73%	157%	64%	76%	39%
	Vitamin A	113%	182%	71%	131%	50%
	Folate	85%	199%	87%	69%	47%

agriculture in water-scarce regions, which is higher than by relieving water stress. Relieving soil fertility stress could turn unproductive green water consumption (evaporated from the soil) into productive (transpiration from crops) for low-input farming systems. The water stress becomes more significant when soil fertility stress is addressed under the additional simultaneous irrigation and fertilization scenarios. By comparing this scenario and the fertilization scenario, small-scale agriculture benefits more from the additional irrigation. This reflects nonlinear interactions between soil fertility stress and water stress and the synergies of relieving both of them, which provides an optimistic outlook for the future of small-scale and large-scale agriculture.

It is important to note that there are large differences between and within countries beyond the comparisons drawn between large-scale and small-scale agriculture and water-scarce and water-abundant regions. Soil fertility stress constrains crop production much more in some developing countries, especially in Sub-Saharan Africa. The crop production may double or even triple in these regions due to the fact that current farming systems are low-input (or subsistence) dominated (Fig. 4).

4. Discussion

4.1. *Unequal distribution of water scarcity and food insecurity risks*

Our results reveal the unequal distribution of water scarcity and food insecurity risks between small-scale and large-scale agriculture. Most small-scale agriculture is located in water-scarce regions with greater geographic exposure to water scarcity. In addition, small-scale agriculture is generally equipped with fewer irrigation facilities and uses lower amounts of other inputs reducing their adaptive capacity to water scarcity and droughts. Farmers in this category, as well as local food systems dependent on them, are therefore highly vulnerable to changes in precipitation patterns and droughts because they generally produce food crops and other cash crops important for their food and livelihood security. On the other hand, large-scale agriculture and associated supply chains are much less exposed to water scarcity risks. Large-scale farms, which are focused more on the production of non-food crops, are more commonly located in water-abundant areas or water-scarce areas with well-developed access to irrigation and also use higher levels of other agricultural inputs such as fertilizers helping to maximize productivity and resilience.

Given these differences, we suggest that efforts to enhance food system resilience must take into account inequalities in access and use of social-ecological resources between food and non-food crops and between small-scale and large-scale agriculture. Addressing water risks faced by small-scale agriculture will require a greater focus on investment in sustainable irrigation development given the current low levels of irrigation in small-scale agriculture in water-scarce regions. Such investments are crucial since climate change is expected to exacerbate the variability and volatility of the green water supply. Yet, current climate finance commitments have rarely focused on improving access to irrigation for small-scale agriculture (Chiriac et al., 2020). However, physical constraints to irrigation should also be considered since increasing water consumption for agriculture may not be sustainable in some water-scarce regions or financially viable with existing levels of soil and land fertility. This would call for more radical transformations, such as the reallocation of irrigation and cropland, and changes in planted crops along with dietary changes (Beyer et al., 2022; Gerten et al., 2020; Rosa et al., 2018; Wang et al., 2024). Yet, many of these transformations may have important social-economic implications for both small-scale and large-scale agriculture.

4.2. *Irrigation versus fertilization for enhancing productivity and resilience*

The overall increases in crop and nutrient production with additional irrigation and/or fertilization suggested by our results agree with existing studies, which also indicate that soil fertility stress overweighs water stress even in water-scarce regions (Elliott et al., 2014a; Giller et al., 2022; Langhans et al., 2022; Mueller et al., 2012; Rockström et al., 2003; Rosa et al., 2018). This is especially true for small-scale agriculture as suggested by our results. Consequently, irrigation development projects for small-scale agriculture, aiming to ensure production stability under drought and to support adaptation to climate change (Pörtner et al., 2022), should be accompanied by efforts to improve soil fertility. The reasons for water stress (a lack of irrigation facilities) and soil fertility stress (insufficient fertilization) could be natural, e.g., no available water, or socio-economic, e.g., inadequate investment. Identifying the reasons for water and soil fertility stress is beyond the scope of this study. However, no matter for small-scale or large-scale agriculture, the hotspot of farms facing simultaneous water and soil fertility stress is in developing countries, e.g., India, Nigeria, Niger, Brazil, and Ethiopia. It is crucial for them to address both water and soil fertility stress to achieve sustainable development goals.

There are multiple limitations to the expansion of irrigation and the use of fertilizers, especially in the regions where our analysis suggests

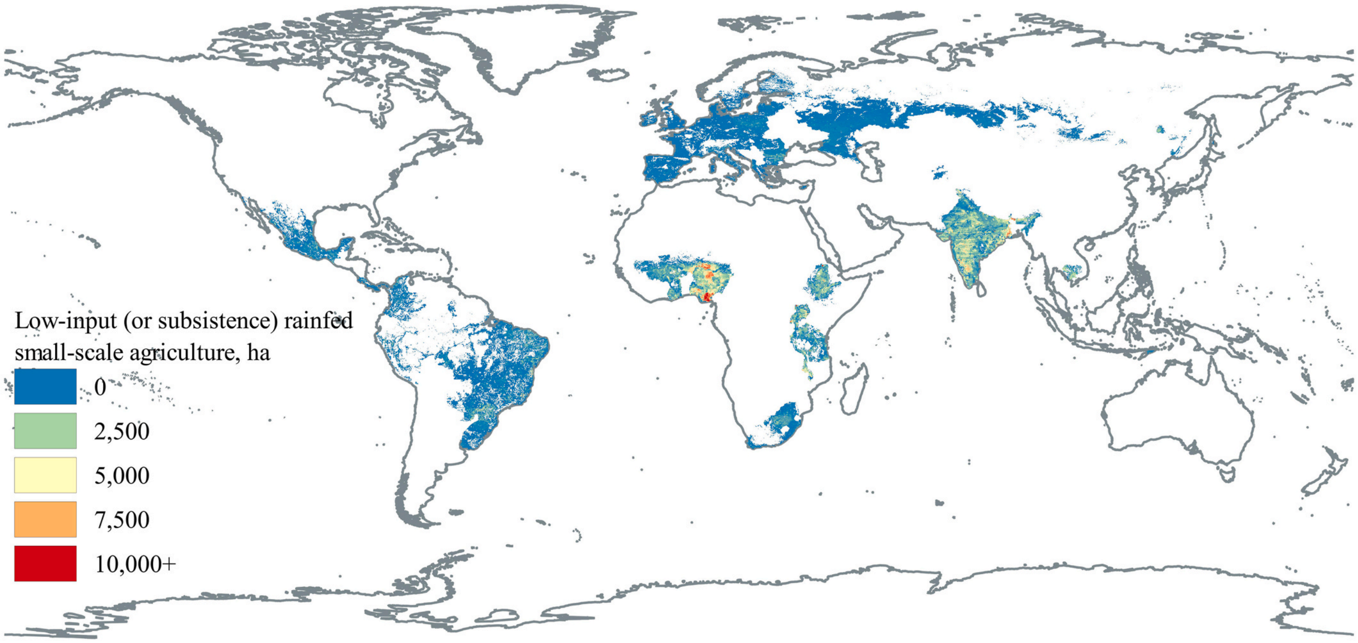

Fig. 4. The distribution of low input (or subsistence) rainfed small-scale agriculture, ha.

these interventions would have the greatest benefits and payoffs (i.e. in water-scarce regions, especially those within lower-income or developing countries). For instance, the high cost of building and maintaining irrigation schemes, land tenure issues, and poor extension services can challenge the development and adoption of irrigation in these regions (Nakawuka et al., 2018). Expansion of blue water use through irrigation or input use intensification in water-scarce regions, such as to address productivity gaps faced by small-scale farms, can reduce the environmental flows required to maintain aquatic ecosystem services. Some of these consequences may be mitigated through efforts to ensure available water is used productively and in a sustainable way e.g., effective scheduling (Phocaides, 2007), deficit irrigation (Geerts and Raes, 2009), water reuse (Ungureanu et al., 2020), targeting of water to most sensitive and valuable crops (Playán and Mateos, 2006), and rain harvest (Mubiru et al., 2018). However, caution must be taken to ensure that field-level improvements in water management do not translate to more water consumption at the basin level (i.e. irrigation efficiency paradox (Grafton et al., 2018)).

At the same time, interventions to intensify fertilizer use to address poor soil fertility have potential environmental consequences beyond their contributions to changing green and blue water consumption. The increased use of fertilizers, particularly chemical fertilizers, could lead to leaching, water pollution, and emissions. Yet, improved water management, optimal use and timing of fertilizer application, crop rotations, and the use of organic soil amendments can reduce the negative impacts (Bijay and Craswell, 2021). At the same time, the adoption and proper use of fertilizers are affected by limited access to capital and markets, inadequate knowledge about proper nutrient management practices (amount and timing of application), and the absence of soil tests (Saito et al., 2019). Extension services will be key to support sustainable and effective input management, especially for small-scale farmers who have shown a tendency to overuse fertilizers when they adopt them (Ren et al., 2019; Wu et al., 2018). Furthermore, there is a need to ensure that irrigation and fertilizer interventions or policies occur in tandem and not independently, without which evidence suggests that investments may fail to deliver intended gains in productivity or climate resilience (Higginbottom et al., 2021; Redicker et al., 2022). We did not analyze these aspects of sustainability or limitations in the use of fertilizers and irrigation expansion, but these are important questions that can help inform decision food system transformations.

4.3. Limitations and uncertainties

Our definition of small-scale agriculture may lead the identified small-scale agriculture in one country to have different sizes than in another country. This is because we combined both country-dependent and country-independent definitions to separate small-scale agriculture and large-scale agriculture (SI Appendix, S3). This means that the farm size of small-scale agriculture in the USA or Europe may be larger than the size of the large-scale agriculture in some African countries. However, combining definitions is still necessary in order to comprehensively identify small-scale agriculture given no standard definition at the global level available. We try to give sufficient attention to small-scale agriculture considering both the differences between countries and the differences within a country.

When using the crop model to estimate water consumption and yield, the main drivers included in this study are climate, soil characteristics, crop types, soil fertility, and types of water supply, which could explain major global yield variability (Cecil et al., 2023; Mueller et al., 2012; Ray et al., 2015). Compared to previous studies, we have included more factors that differentiate small-scale and large-scale agriculture, e.g., input level and type of irrigation. There are still other factors that may differentiate small-scale and large-scale agriculture that are not included in our simulation because of data availability limitations at the global level, e.g., soil penetrability, access to better crop varieties, and pesticide management. The results may also suffer some limitations and uncertainties resulting from the input datasets, for more information please refer to Mialyk et al. (2024).

We assume the same field practices for small-scale and large-scale agriculture if they belong to the same farming system. At the same time, we acknowledge that agriculture is highly diverse within broad categories of small-scale and large-scale agriculture adopted in our study (e.g. as evidenced by Frelat et al. (2016)). At the global level, it is challenging to include all of these factors due to limited consistent data availability on the characteristics of farms beyond their size and levels of input use intensity. Our results on the differences between small-scale and large-scale agriculture are driven by the differences among farming systems rather than within farming systems. Our results may underestimate the water consumption and yield variability within the same farming system between small-scale and large-scale agriculture. Nonetheless, our results demonstrate that stark differences exist between small-scale and large-scale agriculture in terms of their contributions and exposure to water scarcity, linked to broad differences in the socio-ecological characteristics of these farm types. Though we do not expect the differences within one farming system to outweigh the differences among farming systems at the global scale, future studies will better assess the effects of farm size differences by considering more factors when data is available.

Our groundwater level representation is limited because we cannot consider the effects of pumping locations, spatial variations in aquifer depths within grid cells, or proximity to water bodies (de Graaf et al., 2019). Our estimations on the contribution of capillary rise to total water consumption may therefore be uncertain, but formally assessing and quantifying these uncertainties is beyond the scope of available data given that many regions globally lack spatially detailed networks of groundwater level monitoring.

Our results at the grid level may suffer more uncertainties and limitations than those at the regional or global level. The small-scale and large-scale agriculture distribution at the grid level may be to some extent uncertain. As discussed by Su et al. (2022) where we retrieved the crop-specific and farm-size-specific data, the country-level and global-level observations are robust to grid-level uncertainties.

Uncertainties on water scarcity distribution may be introduced because of the inconsistencies in crop water consumption between our results and the water scarcity index database. We recalculated the water scarcity index using our crop water consumption by deriving water availability and non-crop water consumption from the water scarcity index database (Mekonnen and Hoekstra, 2011b, 2016). Water consumption from 18 main crops was used as an approximation of crop water consumption due to data availability (Mekonnen and Hoekstra, 2011a). Based on the recalculated water scarcity index, we found that inconsistencies in crop water consumption only affect the water scarcity classifications of less than 4% of grid cells. Our main conclusions may be insensitive to these inconsistencies.

We cover 55 countries which cover 61% of the global harvested area (about half if we exclude fodder crops). They represent both developing and developed countries from all the continents except Oceania and Antarctica. We therefore do not expect our main conclusions will change if more data becomes available for other countries. Moreover, comparisons with other global studies by this study and previous studies (Ricciardi et al., 2018) indicate that 55 countries well represent the global statutes on small-scale and large-scale agriculture. Current conclusions are unlikely to change with better data availability though it could increase the confidence of current conclusions.

5. Conclusion

Our process-based crop production and water consumption estimates show small-scale agriculture contributes less to nutrient production considering their harvested area despite small-scale agriculture cultivating more food crops (relative to their total harvested area) than large-scale agriculture. This result challenges the assumption made by existing global scale studies when allocating national agricultural production to small-scale and large-scale agriculture, which ignores the differences in climate conditions, soil characteristics, input level, and type of irrigation that they may have. The lower contribution of small-scale agriculture is due to both water stress and soil fertility stress. Small-scale agriculture faces more water scarcity while consuming less surface water and groundwater compared to their larger counterparts due to a lack of irrigation facilities. Soil fertility stress severely limits small-scale agriculture's ability to use green water (rainwater) productively, resulting in 70–90% of global unmet crop production potential in water-scarce regions. Understanding such disparities is a necessary step toward enhancing the equity, resilience, and sustainability of agricultural systems worldwide.

CRediT authorship contribution statement

Han Su: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Timothy Foster:** Writing – review & editing, Writing – original draft, Software, Methodology, Conceptualization. **Rick J. Hogeboom:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Diana V. Luna-Gonzalez:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Oleksandr Mialyk:** Writing – review & editing, Software, Methodology. **Bárbara Willaarts:** Writing – review & editing, Supervision, Conceptualization. **Yafei Wang:** Writing – review & editing, Conceptualization. **Maarten S. Krol:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2025.100844.

Data availability

The country-level and grid-level output of this study is freely available via a Creative Commons Attribution 4.0 International license at the DOI: 10.4121/de21d6c2-95f7-42e5-a3cf-f5b66b559924. It contains crop production, water consumption, soil fertility index, and nutrition production divided by small-scale or large-scale agriculture, crop, water-scarce or water-abundant regions, and farming system. ACEA source code used in this study is freely available on GitHub (https://github.com/Han-Su22/ACEA). All the past and future published versions of ACEA are archived via Zenodo (DOI: 10.5281/zenodo.10510933) via a Creative Commons Attribution 4.0 International license. All the code, input data, and output data required to reproduce the results in this study will be archived for at least 10 years after publication within the University of Twente, Multidisciplinary Water Management (MWM) group. The MWM group will make those available upon request

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