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LETTER

# Different places, different challenges: mapping global variations in agrifood-system burdens

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## Abstract

The global agrifood system is central to many challenges humanity faces today. Despite significant growth in total production, it fails to ensure food security for all, drives biodiversity decline, and majorly contributes to climate change. Research on agrifood-system burdens often focusses on the national level and isolated burdens, ignoring their systemic complexity. We address this knowledge gap by combining global subnational datasets proxying four key dimensions of agrifood-system burdens: environmental footprint, climate change, income poverty, and malnutrition. We map global hotspots of co-occurring agrifood-system burdens for 2017. We overlay these with data on ambient population counts, agricultural areas, farm size distributions, and lands inhabited by Indigenous peoples to identify spatial correspondence between people in vulnerable contexts and food production regions facing these burdens. We further assess countries' relative burden against their inequality and governance indicators. Burden hotspots occupy many regions worldwide, especially in low-income, (sub)tropical regions. Single burdens occupy regions harbouring about 5 billion people (∼66% of the global population) and 1.8 billion ha of agricultural lands (∼40%), while multiple burdens occupy regions with about 1.9 billion people and 470 million ha agricultural lands. Environmental footprint is the strongest contributor to these burden profiles. Regions with traditionally marginalised communities (i.e. small-scale farmers and Indigenous peoples) disproportionally face multiple burdens. Agrifood-system burdens are more prevalent in countries with higher economic inequality and poorer governance. Burden profiles vary substantially within and between countries, necessitating regionalised and context-specific policies for effective, bundled, and targeted solutions. Addressing agrifood-system burdens can also synergise with tackling other current global challenges, like biodiversity loss and environmental justice.

## 1. Introduction

While the global agrifood system has substantially increased production volumes over the last decades (Godfray *et al* 2010, FAO 2023), it faces numerous challenges and geographically heterogeneous burdens. It exerts strong pressures on the environment through increased greenhouse gas emissions (IPCC 2019, Crippa *et al* 2021), pesticide and nutrient leaching (West *et al* 2014, Maggi *et al* 2019), freshwater consumption and pollution (Hoekstra and Mekonnen 2012), soil erosion (Borrelli *et al* 2017), and habitat destruction or degradation and associated biodiversity loss (IPBES 2019, Benton *et al* 2021). Agrifood systems both contribute to climate change and are affected by it, especially through more frequent extreme weather events (IPCC 2023a). These events damage food production (IPCC 2023b), resulting in substantial yield losses (Heino *et al* 2023) and societal costs (Newman and Noy 2023). We hence understand burdens as cumulative, often negative, pressures that the global agrifood system imposes on social–ecological systems. Burdens, as unintended consequences of agrifood-system activities, can strain environmental resources, human well-being, and societal structures.

Simultaneously, the global agrifood system, itself a system of local and regional agrifood systems, fails to meet peoples' needs in terms of nutrition and affordability, leaving about 800 million people undernourished and over 3 billion unable to afford healthy food (FAO, IFAD, UNICEF, WFP, WHO 2022), while overweight and obesity affect about 2.6 billion people (WOF 2023). Food insecurity often stems from the intertwined relationship between malnutrition and poverty, even within food producing households, creating a vicious cycle of sustained, poverty-limited food access (Tanumihardjo *et al* 2007, Siddiqui *et al* 2020). Moreover, highly specialised, input-dependent, and monoculture-dominant agrifood systems can lack resilience, increasing food insecurity in affected regions (Mehrabi and Ramankutty 2019, Egli *et al* 2020, Clapp 2021).

Impacts of agrifood systems particularly threaten populations with low agency, at risk of exploitation through global commodity markets, or with low financial capacity. This includes, for example, small-scale farmers, fishers, pastoralists, hunter gatherers, and Indigenous peoples (IFAD/UNEP 2013, Díaz *et al* 2019), increasing their susceptibility to food insecurity (Harvey *et al* 2014). Such communities also face risks of ecological marginalisation (Levers *et al* 2021), displacement (Kennedy *et al* 2023), poverty traps (Woodhill *et al* 2022), or climate change impacts from agrifood systems (Morton 2007). Simultaneously, small-scale farmers are key for global food production (Ricciardi *et al* 2018) and Indigenous peoples play crucial roles in both food production and resource stewardship (Kuhnlein *et al* 2013).

Agrifood-system indicators and their impacts on social–ecological systems are well-documented. Global indicator maps support assessments of agrifood-system (un)sustainability (Béné *et al* 2019, GAIN 2024), including monitoring progress toward global policy goals such as the Sustainable Development Goals or the Global Biodiversity Framework (Schneider *et al* 2023). Extensive research assesses agrifood-system burdens, including environmental impacts (Poore and Nemecek 2018, Halpern *et al* 2022), malnutrition (Kinyoki *et al* 2020, GNR 2021), and extreme weather events (Gaupp *et al* 2019). Other studies explore pathways to more sustainable and healthier agrifood systems, aiming to balance food and nutrition security with reduced environmental impacts (e.g. West *et al* 2014, Erb *et al* 2016, Springmann *et al* 2018a, 2018b).

Global analyses of combined agrifood-system burdens have been scarce, largely due to insufficient spatial resolution and coverage of relevant data, a common challenge in agrifood-system research (Kebede *et al* 2024). Most studies either provide national-level data (e.g. Béné *et al* 2019), overlooking subnational variability and masking burden hotspots (i.e. areas of exceptionally high burdens), or focus on individual agrifood-system dimensions at finer scales (e.g. Halpern *et al* 2022), neglecting the complexity and interconnected nature of agrifood-systems (Zhang *et al* 2024, Schneider *et al* 2025). This impedes systematically identifying where and how agrifood-system burdens overlap, estimating populations and agricultural areas facing burdens, and developing context-specific, place-based solutions to support at-risk communities (Fanzo *et al* 2024).

To address these limitations, we first identify global hotspots of four key agrifood-system burdens at the subnational level for 2017, using the most up-to-date, spatially-explicit data sources on indicators representing: (1) environmental pressures from food production systems, (2) extreme weather events affecting food production systems, (3) malnutrition (over- and undernutrition), and (4) income poverty (table 1). Second, we examine the spatial distribution of hotspot combinations and estimate the population and the agricultural area co-occurring with individual and combined burdens. Third, we assess burdens co-occurring with different farm-size categories and lands inhabited by Indigenous peoples. Lastly, we relate burden hotspots to country-level inequality and governance indicators. Each of these four objectives helps to advance beyond the current state-of-the-art and contributes to a deeper understanding of agrifood-system burdens.

Our aim is to highlight agrifood-system burden exposure without assessing adaptive capacity or

**Table 1.** Overview and description of input data used for mapping global agrifood-system burdens.

| System | Burden indicators | Description | Unit | Source | Year | Resolution |
|---|---|---|---|---|---|---|
| Ecological | Environmental footprint | Cumulative index based on GHG emissions, freshwater use, habitat disturbance, and nutrient pollution from terrestrial food production. | (·) | Halpern *et al* (2022) | 2017 | 5 arcmin |
| | Weather extreme events | Weather extremes affecting agricultural systems through too dry, wet, hot, and cold conditions. | | Own calculation based on ERA5 data from Hersbach *et al* (2020) | 2017 (2014–2020) | 0.25° |
| | | Droughts: longest period of consecutive dry days with precipitation sum $<1$ mm $d^{-1}$ (CDD). | (days) | | | |
| | | Wetness: monthly maximum 5 d precipitation (RX5). | (mm) | | | |
| | | Heat: days with maximum temperature above 35 °C (TX35). | (days) | | | |
| | | Cold spells: days with minimum temperature below 0 °C (FD). | (days) | | | |
| Social | Malnutrition | Double burden of malnutrition based on the prevalence of childhood overweight and wasting in Low- and Middle-Income Countries. | (%) | Kinyoki *et al* (2020) | 2017 | 5 arcmin |
| | Income poverty | Gross national income per capita with purchasing power parities (PPP) in 2011 US$ (v5). | (US$) | Smits and Permanyer (2019) | 2017 | Subnational administrative units |

implying causality or impact direction. Burdens can either result from or affect agrifood systems, but require place-based solutions in both cases. While we map the diversity of burden types and profiles across regions, we do not discern spatial links between burden causes and impacts. Some burdens may originate in distal regions, while other burdens may have spill-over effects elsewhere (Liu *et al* 2013). By covering both drivers and impacts, our indicators capture active (locally caused) and passive (externally caused) components of burdens in hotspot areas.

## 2. Materials and methods

### 2.1. Data for mapping global agrifood-system burdens

We collected global data to represent four key dimensions of agrifood-system burdens for the target year 2017 (table 1): (1) environmental footprint of food production and (2) weather extremes affecting food production systems (ecological burdens), and (3) income poverty and (4) double burden of malnutrition (social burdens). These dimensions broadly align with key themes for holistic agrifood-system monitoring (Schneider *et al* 2023). We harmonised all indicators to a 5-arc minute resolution (figure S1). Our spatially-explicit approach captures ecological burdens at their origin, not where they take effect. For example, $CO_2$ emissions from rice production or livestock originate locally but can have regional to global impacts, whereas excess nutrients originate locally and mainly have local impacts.

We represented poverty by using income poverty for the year 2017, expressed as gross national income per capita with purchasing power parities (PPP) in 2011 US$ (Smits and Permanyer 2019, Permanyer and Smits 2020). Income poverty strongly correlates with the subnational human development index (SHDI), which includes additional poverty dimensions (World Bank 2023): education and health (figure S2). Due to established thresholds for income poverty (World Bank's international poverty line) and the lack thereof for the SHDI, we used income poverty in our analysis. We used the original GNI values in 2011 PPP, rather than extrapolating them to our target year 2017, to avoid potential conversion bias due to imprecise conversion factors or inconsistent inflation rates. We validated the consistency of 2011 PPP values with 2017 PPP values, demonstrating a high correlation between the two (figure S2), which supports the use of the original 2011 PPP data as a reliable proxy for representing 2017 economic conditions. For malnutrition, we used the prevalence of wasting and overweight among children under 5 years (i.e. double burden of malnutrition) to not limit our analysis to undernutrition, but also include overnutrition. We used malnutrition data for the year 2017 (Kinyoki *et al* 2020), the only available spatially explicit data set covering both burdens of malnutrition.

We represented the environmental footprint of food production by using the cumulative pressure from *disturbance* (proportion of native plants and animals displaced by agriculture [$km^2$eq]), *freshwater use* (total blue water consumption [$m^3$ water]), *excess nutrients* (nitrogen and phosphorus inputs [tonnes NP), and *greenhouse gas emissions* [$CO_2$eq] from food production for the year 2017 (Halpern *et al* 2022). Each pressure was estimated for 26 crop and 19 livestock types using maps on production intensity (see Halpern *et al* (2022) for details). The cumulative pressure index combines rescaled per-food pressure maps and shows each grid cell's proportional contribution to global pressure. This allows comparisons among regions and pressures to identify overlapping pressures and hotspots geographies (Halpern *et al* 2022). This data set covers environmental pressures of 99% of the reported global food production and is the most recent, spatially explicit, and comprehensive for environmental agrifood-system pressures.

We represented climate impacts on agrifood systems by using indicators for weather extremes affecting food production systems (Heino *et al* 2023) from the ERA5 reanalysis (Hersbach *et al* 2020): consecutive dry days (CDD) with precipitation sum $<1$ mm $d^{-1}$, monthly maximum 5 d precipitation (RX5), days with temperatures above 35 °C (TX35), and frost days (FD) below 0 °C. We calculated z-scores between climatologies of the period 1980–2009, following standard climatological practice of using a 30 year baseline to estimate historical climate conditions, and each year for the period 2014–2020, resulting in seven difference maps between historic and current conditions. We then calculated median z-scores for each weather extreme indicator for 2014–2020, considering all months for tropical regions and summer months for temperate regions as generic growing seasons. We included 3 years before and after 2017 (target year) to average-out anomalous single-year impacts. We used standard extreme weather indicators as they minimise distributional assumptions and allow consistent and comparable applications across diverse climatic regions. More complex metrics like SPI, SPEI, or soil moisture anomalies require careful calibration to local conditions, which can lead to uncertainties in their calculation, for example stemming from choices regarding the probability distribution and observational window (Wang *et al* 2021, Laimighofer and Laaha 2022).

### 2.2. Hotspot mapping

We mapped global hotspots of agrifood-system burdens using indicators representing both, social and ecological systems (figure 1). We defined hotspots as areas where indicator values exceed a certain threshold, indicating exceptionally high levels. Hotspot mapping is hence straightforward and intuitive, and allows sensitivity analyses on the selected thresholds (Schröter *et al* 2017).

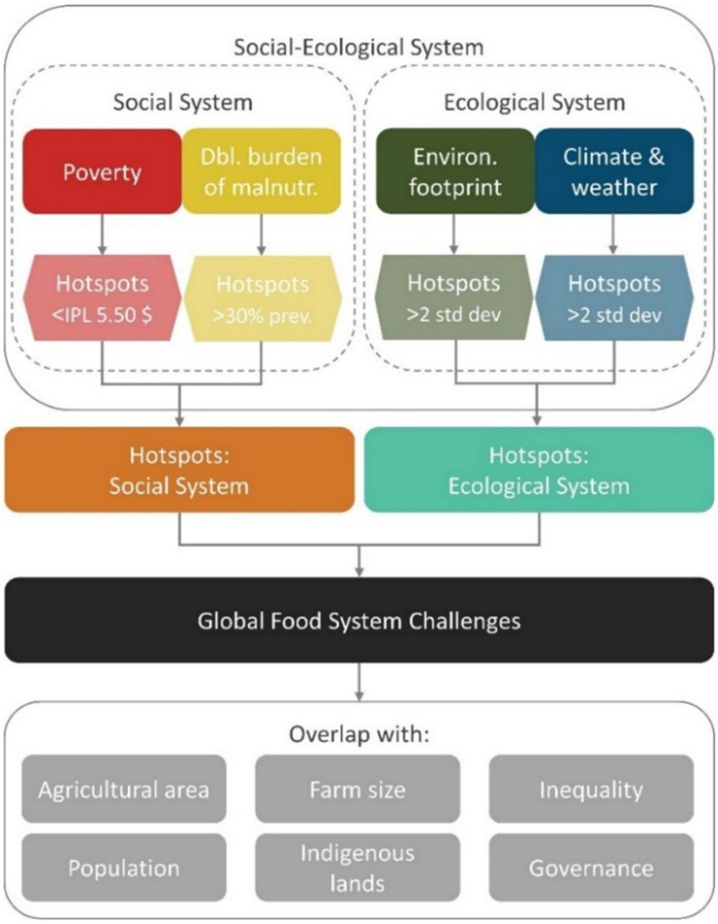


**Figure 1.** Analysis workflow for mapping global agrifood-system burdens. For a conceptual framework illustrating the theoretical relationships and feedbacks between burden dimensions, please refer to figure S3.

We used a three-stage approach to map global burden hotspots, and interpreted their spatial patterns based on geographic world regions (FAO, IFAD, UNICEF, WFP, WHO 2022). First, we mapped binary hotspots for each burden (table 1, figure S4). We used a thresholding approach based on standard deviations for environmental pressures and weather extreme events, defining hotspot regions being (more than) two standard deviations above the global average. 95% of a normally distributed data population fall within two standard deviations of the mean (about 68% within one standard deviation), allowing reliable hotspot detection. This approach better accounts for potentially different indicator data distributions than quantile-based approaches (e.g. Kuemmerle *et al* 2016, Halpern *et al* 2022), which would result in a fixed number of data points, and hence hotspots, per quantile and indicator. For weather extremes, we combined individual hotspot maps (i.e. droughts, wetness, heat, cold spells) into an overall extreme events hotspot map using a logical 'or'. To identify malnutrition hotspots, we used a prevalence threshold of $\geqslant$15% (de Onis *et al* 2019). For poverty, we used the World Bank's international poverty line of $\leqslant$5.50 US$ PPP (Ferreira *et al* 2015, Jolliffe and Prydz 2016), thus covering poverty in Low- and Middle-Income Countries (Schoch *et al* 2020). Second, we combined binary hotspot maps into a single map with sixteen classes: from no hotspots to all four burdens. Lastly, we thematically grouped burden hotspots based on indicator combinations and the differentiation into social and ecological systems (figure 1, table S1). Indicators are generally weakly correlated (figure S5), and we interpreted the spatial overlap of their hotspots as their association.

### 2.3. Impact analyses

We overlaid our final hotspot map with 2017 ambient population counts (Rose *et al* 2018) and agricultural area data covering rainfed and irrigated cropland, cropland with herbaceous and tree-shrub crops, mosaic cropland, mosaic herbaceous cover, and grassland (C3S-CDS 2019), to estimate the population and food production area located in hotspot regions of agrifood-system burdens. Population estimates reflect the spatial co-occurrence with burden hotspots, not the number of people directly affected by burdens, which is likely lower.

Furthermore, we assessed burden exposure across farm sizes using a global map of dominant farm size (Mehrabi and Ricciardi 2024), categorised as very small (0–2 ha), small (2–20 ha), medium (20–100 ha), and large to very large farms (>100 ha). We also analysed burden distributions within and outside lands inhabited by Indigenous peoples (Garnett *et al* 2018). Areas not mapped as 'Indigenous' should not be assumed to lack Indigenous populations, but rather lack publicly available spatial data indicating their presence (Garnett *et al* 2018).

Finally, we calculated the percentage of each country's area falling within burden hotspots and related this to inequality and governance indicators. We estimated within-country inequality using the Gini coefficient based on adult pre-tax national income (Alvaredo *et al* 2022), and governance by the average of all six worldwide governance indicators (Kaufmann and Kraay 2023), both for 2017. High pairwise correlations among indicators (Spearman rho: 0.67–0.93) supports the robustness of our aggregated governance index.

## 3. Results

### 3.1. Spatial patterns

Global agrifood-system burden hotspots show distinct geographical patterns (figures 2 and S6). Hotspots of co-occurring 'Social' and 'Ecological' burdens are rare and located in Sub-Saharan Africa. Hotspots of 'Social' burdens (poverty and malnutrition, sometimes co-occurring with hotspots of an 'Ecological' burden) occur in Sub-Saharan Africa, particularly Central and Eastern Africa. Hotspots of 'Ecological' burdens (environmental and climate, sometimes co-occurring with hotspots of a 'Social' burden) are dispersed across the world, with regional clusters in Southern, Eastern, and Central Asia, the central part of South America, Western Africa, and the Mediterranean. 'Crossover' hotspots (co-occurring hotspots of one 'Social' and one 'Ecological' burden) predominate in Western and Central Asia (poverty and climate, poverty and environment), Eastern Africa (poverty and environment, malnutrition and climate), Southern Asia (malnutrition and environment), and Eastern Asia (malnutrition and environment, malnutrition and climate). Single hotspots of agrifood-system burdens are evident in various world regions (figure 2, text S1). A sensitivity analysis using less strict thresholds (one SD above global average for both ecological burdens, ⩾10% prevalence for malnutrition, ⩽21.70 US$ PPP for poverty) yields geographically and thematically similar results (figures S7 and S8).

### 3.2. Overlap with population and agricultural area

Almost 5 billion people (about two-thirds of the 2017 world population) inhabit regions characterised by agrifood-system burden hotspots, of which about 1.9 billion people (∼25% of the world population) inhabit regions with multiple burdens (figure 3, table S2). Importantly, this means not all these people are directly exposed, but that burdens occur where they reside. About 1.8 billion people inhabit regions with two co-occurring burdens (of which ∼1.4 billion with co-occurring environmental pressures and malnutrition), about 85 million with three (of which ∼73 million with co-occurring environmental, malnutrition, and weather extremes), and less than 1 million with all four burdens. Of single burdens, about 2.3 billion people (∼30% of the world population) inhabit regions with environmental pressure, 380 million with malnutrition, 210 million with income poverty, and 170 million with weather extreme hotspots.

While about 60% of the global agricultural area is not located within any burden hotspot (∼2.8 billion ha), about 10% (∼470 million ha) lies in regions with multiple burdens (figure 3 and table S2): about 450 million ha with two co-occurring burdens (of which ∼270 million ha with co-occurring environmental pressures and malnutrition), about 16 million ha with three co-occurring burdens (of which ∼8.5 million ha with co-occurring environmental, malnutrition, and weather extremes), and less than 1 million ha with all four burdens. Of single burdens, about 630 million ha (∼13%) are located in regions with environmental pressure, about 290 million ha with weather extreme, about 280 million ha with malnutrition, and about 180 million ha with poverty hotspots.

### 3.3. Relationship to farm size

Examining the geographies of agrifood-system burdens by farm size, three main insights emerge: first, hotspots of double (∼1.2 billion people and ∼265 million ha agricultural area), triple (∼65 million people and ∼10 million ha), or quadruple (less than 1 million people and ha, respectively) agrifood-system burdens occupy regions characterised by very small farms (<2 ha), mostly pertaining to 'Ecological' burdens (figure S9 and table S3). Moreover, about 1.9 billion people and 570 million ha of agricultural area are located in hotspots of single burdens in these regions, mostly comprising of environmental pressures.

Second, environmental pressures and weather extremes are more prevalent in regions characterised by large to very large farms (>100 ha), contributing almost exclusively to the hotspots in these regions (figure S10 and table S3). Regions characterised by very large farms are primarily characterised by burdens from environmental pressures (∼140 million people and ∼160 million ha) and weather extremes (∼30 million people and ∼100 million ha) individually, as well as by their co-occurrence (∼28 million people and ∼17 million ha). The absence of hotspots from poverty and malnutrition in such regions

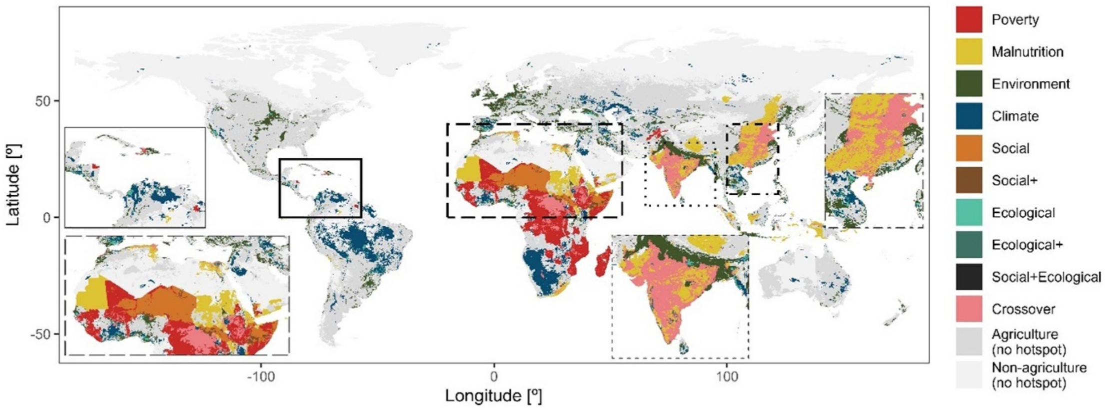


**Figure 2.** Global hotspots of agrifood-system burdens. Social burdens: income poverty ('Poverty'), double burden of malnutrition ('Malnutrition'). Ecological burdens: environmental pressures ('Environment'), weather extremes ('Climate'). 'Social' and 'Ecological' represent combined burden hotspots of 'Poverty' and 'Malnutrition', and 'Environment' and 'Climate', respectively. 'Social+' and 'Ecological+' indicate 'Social' or 'Ecological' burden hotspots, respectively co-occurring with a single burden hotspot of the other system (i.e. 'Environment' or 'Climate' with 'Social' burden hotspots, or 'Poverty' or 'Malnutrition' with 'Ecological' burden hotspots). 'Social + Ecological': combination of all four burden hotspots. 'Crossover': co-occurrence of single 'Social' and 'Ecological' burden hotspots. 'Agriculture (no hotspot)' and 'Non-agriculture (no hotspot)': Agricultural and other non-agricultural areas without any occurrence of agrifood-system burden hotspots. We describe the thematic grouping of individual hotspot types in table S1. Inlets show regions characterised by multiple co-occurring agrifood-system burdens (line types link focus regions and inlets). Hotspots of 'Environment' and 'Climate' burdens: regions that are (more than) two standard deviations above the global average. Hotspots of 'Malnutrition': regions above a prevalence threshold of 15%. Hotspots of 'Poverty': regions below the World Bank's International Poverty Line threshold of 5.50 US$ PPP.

is understandable, as larger farms typically develop in regions of good economic and infrastructural conditions, or are the results of this (Deininger and Byerlee 2012, Mehrabi 2023).

Third, in regions characterised by small to very small farms, agrifood-system burdens, especially 'Ecological' burdens, overlap disproportionally more with people than with agricultural area for each farm size category, when normalising the number of people by the agricultural area in these regions (figure 4). Importantly, although there are more small farms than large farms globally, the area occupied by large farms is much higher than the area occupied by small farms (Lowder *et al* 2021).

### 3.4. Indigenous peoples

Overlaying hotspots of agrifood-system burdens with spatially explicit information on lands managed and/or controlled by Indigenous peoples (Garnett *et al* 2018) shows that their area share, compared to regions for which an Indigenous connection cannot be inferred based on publicly available geospatial data, increases with increasing co-occurrence of burden hotspots (figure 5). Moreover, regions with lands managed and/or controlled by Indigenous peoples show a stronger overlap with 'Social' compared to 'Ecological' burdens. The share of Indigenous lands overlapping with hotspots of 'Social' or 'Ecological' burdens that co-occur with a hotspot of the other system (i.e. 'Crossover' burdens) is larger than for 'Social' or 'Ecological' burdens alone.

### 3.5. Inequality and governance

Hotspot area shares per country exhibit strong heterogeneity across both economic inequality and governance (figure 6). The country area share of burden hotspots generally increases with increasing inequality (along with larger variability within inequality levels), particularly for regions characterised by single and, to a lesser degree, double burden hotspots (figure 6(A)). The area shares of triple and quadruple burden hotspots is negligible. For single burden hotspot regions, we observe an increase in area shares of poverty- and climate-related burden hotspots with increasing inequality (figure 6(B)). Area shares of burden hotspots related to environmental pressures increase with decreasing inequality. Within-category variability generally decreases with increasing inequality, except for climate-related burden hotspots.

Hotspot area shares per country are generally higher in countries with poorer governance, especially for single and, to a lesser degree, double burden hotspots (figure 6(C)). Across burden hotspots, area shares generally decrease with better governance. Breaking down burden profiles shows a distinct differentiation of individual burdens along the governance gradient. 'Social' burdens (i.e. poverty and malnutrition) have higher area shares in countries with poorer governance.

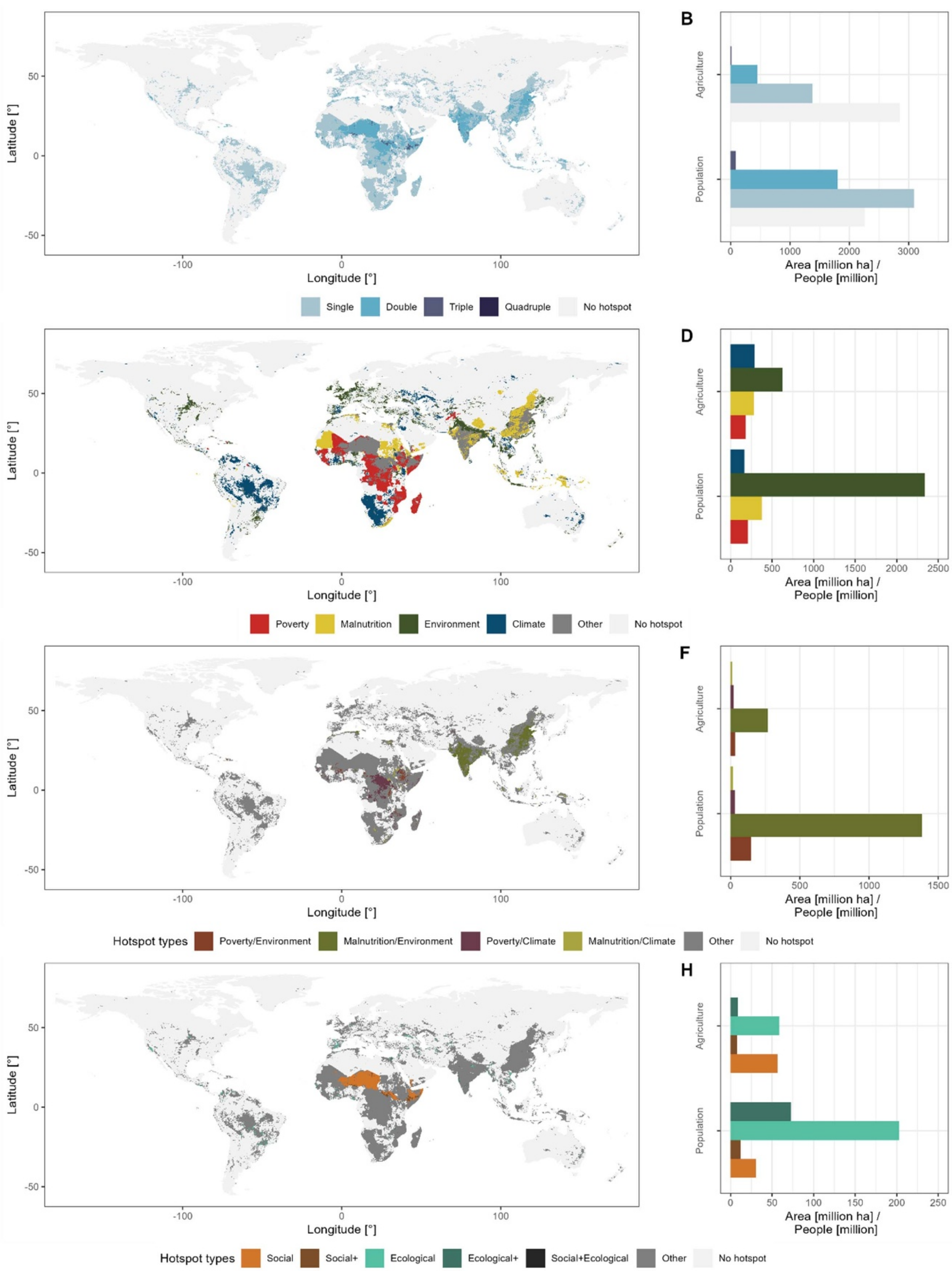


**Figure 3.** Agricultural area and number of people located in hotspot regions of global agrifood-system burdens. Panels (A), (C), (E), and (G) show the geographic distribution of different burden hotspots, Panels (B), (D), (F), and (H) show the agricultural area [million ha] and the number of people [million] spatially overlapping with burden hotspots. Panels A and B focus on any given occurrence of single, double, triple, and quadruple burden hotspots. The subsequent panels 'zoom in', and focus on single burden hotspots (Panels (C), (D)), 'Crossover' burden hotspots (Panels (E), (F)), and all combinations of 'Social/Social+', 'Ecological/Ecological+', and 'Social + Ecological' burden hotspots (Panels (G), (H)).

In contrast, the area share of burdens related to the environmental footprint of food production is higher and increasing in countries with good governance, being the only single burden for countries with fairly good to very good governance (figure 6(D)).

## 4. Discussion

Research on agrifood-system burdens is extensive; however, the regional variability in their manifestation is often under-recognised. Our analysis of global agrifood-system burdens and their

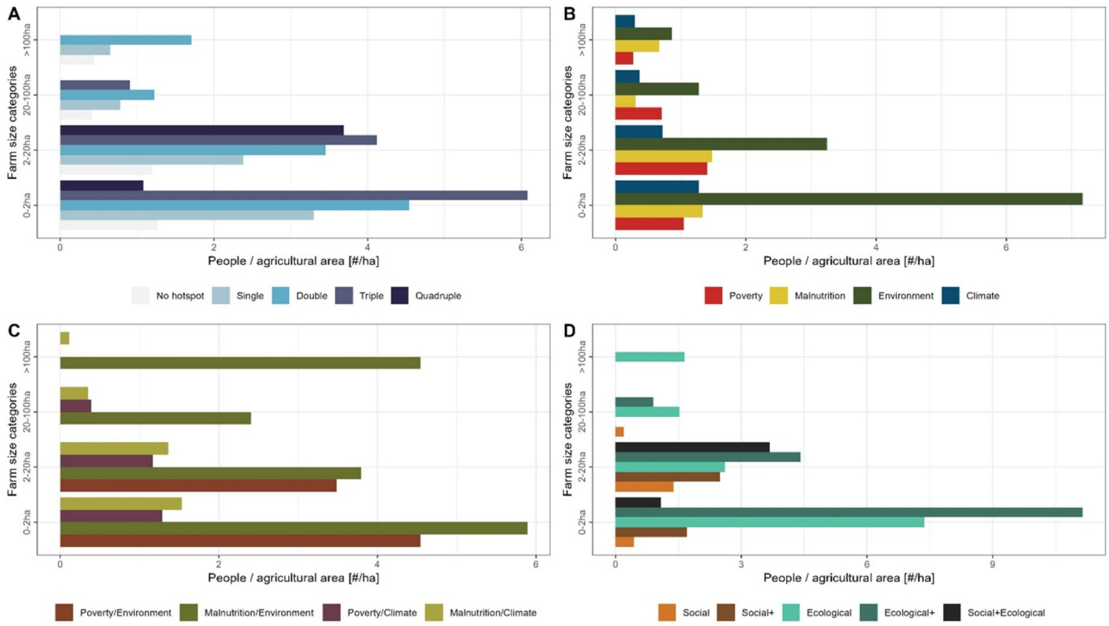


**Figure 4.** Global hotspots of agrifood-system burdens per farm size category. Panels show the number of people normalised by agricultural area [#/ha] co-occurring with burden hotspots, for each farm size and burden hotspot category. Panel (A): occurrence of single, double, triple, and quadruple burden hotspots; Panel (B): single burden hotspots; Panel (C): 'Crossover' burden hotspots, Panel (D): combinations of 'Social/Social+', 'Ecological/Ecological+', and 'Social + Ecological' burden hotspots. Please refer to figures S9 and S10 for visualisations of absolute and relative values, separately for the number of people and agricultural area.

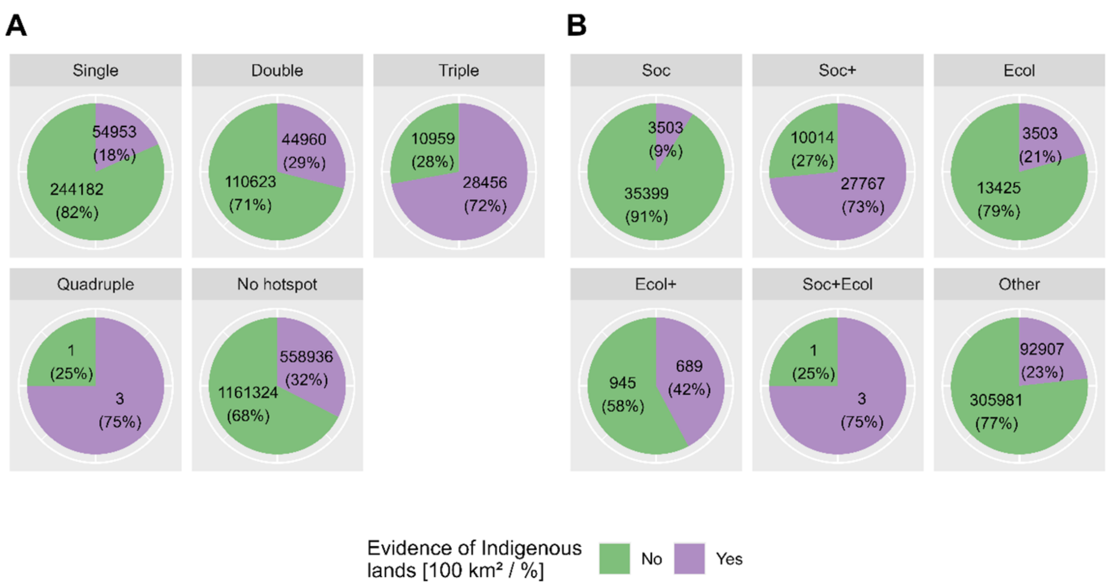


**Figure 5.** Spatial overlap of areas with/without evidence of Indigenous peoples with global hotspots of agrifood-system burdens. We combined individual burden hotspots into single, double, triple, and quadruple burdens (Panel (A)) or any combination of multiple hotspots (Panel (B)). Pie charts represent the spatial coverage for areas with (*Yes*) or without (*No*) lands managed and/or controlled by Indigenous peoples, thereby accounting for different sample sizes per category. Numeric values within each pie chart represent the absolute [100 km$^2$] and relative [%] spatial coverage.

spatial relationships supports five key findings. First, social and ecological burden hotspots co-occur in many regions worldwide, especially in low-income, (sub)tropical regions (table 2; see figure S11 for frequency distributions within temperature regimes, World Bank regions, and World Bank income regions). Second, regions facing multiple burdens harbour disproportionally more people than agricultural area relative to their totals co-occurring with burden hotspots, particularly where small farms are prevalent. Third, small-scale farmers and Indigenous peoples disproportionately inhabit regions facing multiple burden hotspots. Fourth, while multiple agrifood-system burdens are more

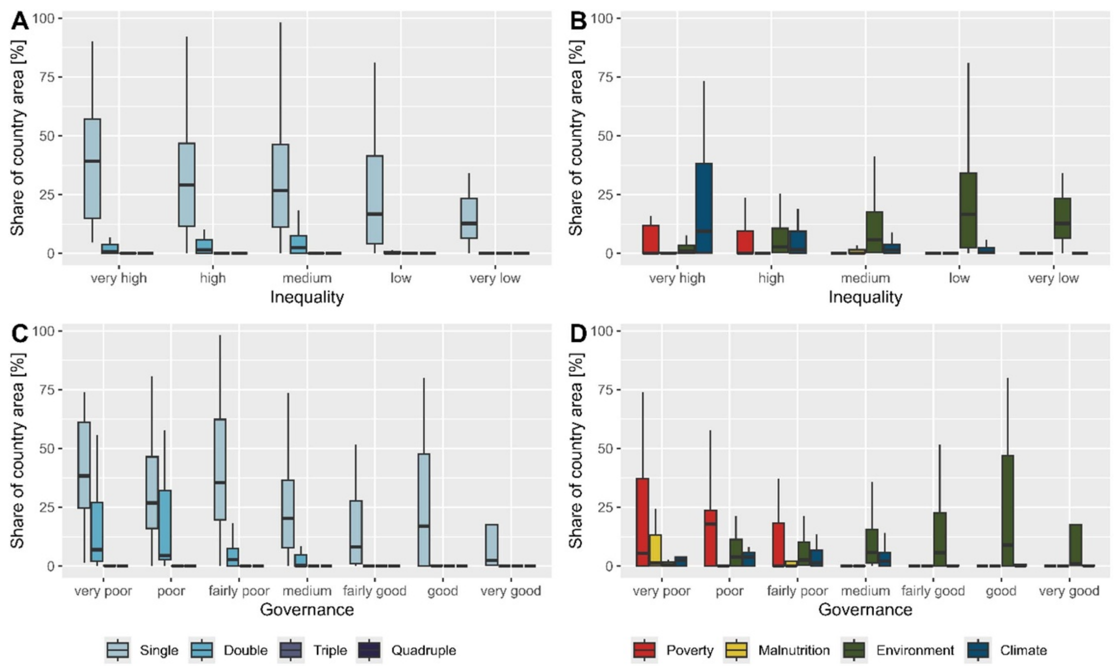


**Figure 6.** Share of global hotspots of agrifood-system burdens per country in relation to inequality and governance. We represent inequality with the Gini coefficient (Panels (A), (B)), governance with the average of all six worldwide governance indicators (Panels (C), (D)), both for occurrence of single, double, triple, and quadruple burden hotspots (Panels (A), (C)), and individual single burden hotspots (Panels (B), (D)). Gini coefficient thresholds: very high = [0.7–1.0], high = [0.6–0.7), average = [0.5–0.6), low = [0.4–0.5), very low = [0.0–0.4). Worldwide governance indicator thresholds: very poor = (∞, −1.5), poor = [−1.5, −1.0), fairly poor = [−1.0, −0.5), average = [−0.5,0.5], fairly good = (0.5,1.0], good = (1.0,1.5], very good = (1.5,∞).

prevalent in countries with higher economic inequality (as might be expected given the role of poverty as an outcome) and poorer governance (as might be expected given the economic relationship that exists globally with these indicators), environmental burdens are more prevalent in locations with supposedly better governance. Lastly, different regions face different burden profiles, therefore requiring different solutions to address them. Our analysis offers insights into the combined effects of climate, food security, poverty, and environmental pressures, aiding decision-makers in creating context-specific solutions to address agrifood-system burdens.

### 4.1. Spatial patterns

The concentration of agrifood-system burden hotspots and associated social–ecological risks in Low- and Middle-Income Countries confirms previous findings. These regions increasingly face multiple burdens where environmental and climate pressures intersect with socio-economic vulnerabilities (Dury *et al* 2019), which confirms studies on climate extremes, food security, and nutrition (FAO IFAD, UNICEF, WFP, WHO 2021, Mirzabaev *et al* 2023), or environmental degradation and poverty (Poverty-Environment Partnership 2008). Our study extends beyond the country or regional level, estimating the number of people and agricultural areas located in regions where compounded burdens take place. Addressing these challenges is complex due to intersecting social and ecological burdens (Levin *et al* 2013), and requires interventions that simultaneously meet local socio-economic needs and preserve ecological integrity.

Our analysis focuses on agrifood-system burdens from environmental pressures, climate change, income poverty, and malnutrition, but other concerns like resource depletion, biodiversity decline, and conflicts can also add to the burden nexuses (FAO, IFAD, UNICEF, WFP, WHO 2021). For instance, conflicts, food prices, and weather extremes are interconnected in 24 African states (Raleigh *et al* 2015). These compound and cascading risks threaten many of the world's most food-insecure, particularly in Africa and Asia (Mehrabi *et al* 2022). Addressing these risks requires systemic approaches; for example, climate policies need to address poverty (Soergel *et al* 2021), and ensure food production beyond baseline (Swinnen *et al* 2022). By integrating social and ecological indicators of agrifood-system burdens, our analysis is a first step in that direction.

### 4.2. Population and agricultural area

Our study shows that regions facing multiple agrifood-system burdens harbour disproportionately more people than agricultural areas, relative to the total number of people and agricultural area co-occurring with burden hotspots. This is unsurprising as over 3 billion people in Low- and Middle-Income Countries, where such hotspots are prevalent, live in rural areas and strongly rely on agriculture for their livelihoods (Woodhill *et al* 2022), a stark contrast to

**Table 2.** Top15 ranking of countries based on their population inhabiting hotspot regions of agrifood-system burdens. We base our ranking on the countries' share of population (2017 data) that co-occurs with regions of multiple agrifood-system burdens (i.e. two or more burden hotspots), and provide the respective population numbers. We calculate the total population for each country based on all grid cells for which we could map burden hotspots. In case of data gaps in the input data, hotspot maps might not include all people inhabiting a country, and hence our calculation might underestimate real population numbers. For 48 countries we could not calculate population numbers and shares because of missing hotspot data, a result of data gaps in the input data.

| Rank | Country | Share of population inhabiting hotspot regions (%) | Number of people inhabiting hotspot regions (million) |
|---|---|---|---|
| 1 | Niger | 91.8 | 17.8 |
| 2 | Egypt | 77.4 | 74.4 |
| 3 | South Sudan | 71.2 | 9.3 |
| 4 | Rwanda | 70.4 | 8.6 |
| 5 | Malawi | 70.0 | 13.3 |
| 6 | Guinea-Bissau | 64.7 | 1.1 |
| 7 | Ethiopia | 59.4 | 62.6 |
| 8 | Togo | 59.1 | 4.6 |
| 9 | Chad | 57.9 | 7.1 |
| 10 | Uganda | 55.9 | 22.0 |
| 11 | Burundi | 55.4 | 6.3 |
| 12 | Haiti | 54.5 | 4.6 |
| 13 | Tunisia | 53.0 | 5.4 |
| 14 | India | 50.7 | 643.6 |
| 15 | China | 50.4 | 686.6 |

High-Income Countries with intensified, large-scale agricultural systems. Another reason is that these hotspot regions are often characterised by small-scale farming (Mehrabi and Ricciardi 2024), and while small farms are more numerous globally, large farms occupy more land (Lowder *et al* 2021). Due to the lack of global, spatially explicit data on farmer population, our estimates based on total population creates an imbalance between densely and sparsely populated food production regions. Addressing sustainability challenges in these regions could leverage the concentration of many people on comparably small agricultural areas. We caution that we assess only the number of people residing in hotspot regions, not the extent to which they are affected. For instance, a 30% malnutrition prevalence threshold means up to 70% of children in those regions may not be directly affected. If children malnutrition reflects population-level food insecurity, the overall affected number of people would likely be similarly lower. Moreover, individual-level impacts depend on household-specific characteristics, adaptive capacity, and access to resources that our analysis cannot capture at this spatial resolution. Future research could refine our analysis by including the agricultural workforce or specific population subsets.

### 4.3. Vulnerable communities

We find that certain communities, such as small-scale farmers and Indigenous peoples, are disproportionately located in hotspot regions of agrifood-system burden. This confirms case study evidence of marginalisation of these groups (IFAD/UNEP 2013, Díaz *et al* 2019). These communities, historically often exploited, often also have less financial capacity (Morton 2007). Considering that small-scale farmers both disproportionately contribute to food security and are among the poorest people (Ricciardi *et al* 2018), the number of people inhabiting hotspot regions of agrifood-system burdens is alarming. Our results may reflect the spatial prevalence of small farms in the (sub)tropics rather than the influence of farm size alone. With the number of small-scale farmers in regions like Sub-Saharan Africa expected to increase (Mehrabi 2023), particular focus is warranted on ways to reduce burdens in this region (Altieri *et al* 2012, Laborde *et al* 2020, Ricciardi *et al* 2021).

We focus on small-scale farmers and Indigenous peoples because their geographically clustered occurrence enables spatial analysis of exposure. In contrast, analysing exposure of other marginalised groups, such as women, youth, or other social groups (Fluit *et al* 2024), is difficult given their integration into societies, requiring detailed local studies. While their sensitivity and adaptive capacity may differ (FAO 2024), for example by occupation, our analysis focuses on exposure, which is not expected to vary spatially for these groups. More generally, our burden dimensions allow linking to populations' vulnerability and resilience (table S4).

### 4.4. Governance and inequality

The generally higher prevalence of burden hotspots in countries with higher economic inequality and poorer governance is concerning, as these factors hinder efforts to overcome food crises (WHH 2023). Interpretations are multifaceted: economic inequality often exacerbates food insecurity and malnutrition by limiting access to nutritious food for low-income populations (FAO & IFAD 2020). Poor governance worsens these issues by failing to implement effective environmental policies and food distribution systems, often in concert with conflicts and low institutional capacities (Boyd and Holly Wang 2011, Candel 2014). The combined effect of high inequality and poor governance affects rural development and agricultural productivity, leading to inefficient food systems and increased agrifood-system burdens (Fanzo and Davis 2021). It also limits access to resources, technology, and markets for small-scale farmers who are crucial for agrifood systems in developing nations (FAO & IFAD 2020). Consequently, transparent and inclusive governance is need to implement policies supporting sustainable agriculture and food security (Janin *et al* 2023).

We find that countries with good governance are characterised by larger and increasing environmental burdens. While better governance is associated with higher agricultural productivity (Lio and Liu 2008), these intensive systems often have strongly negative ecological and social impacts (Foley *et al* 2005). Thus, good governance may not always reduce agrifood-system burden exposure. However, good governance remains crucial for enacting effective policies and regulations (Schneider *et al* 2025).

### 4.5. Data quality and robustness of results

Despite using the most recent, high-quality data, our analysis, like many global studies, has known limitations. Different indicators or dimensions could have been chosen, and our choices consequently influence possible recommendations. We selected indicators based on global scope, sub-national resolution, consistency, thematic fit, and identical target year, resulting in a trade-off between thematic detail and spatial coverage, similar to other global food system analyses (Béné *et al* 2019). Malnutrition estimates are high for China, especially overweight, yet estimates have high uncertainties (Kinyoki *et al* 2020). As uncertainty estimates were not available for all datasets, we could not perform a formal uncertainty analysis. Notably, malnutrition data covers children under 5 years and was unavailable for many High-Income Countries, despite their evident malnutrition issues (GNR 2020), which explains the deviation of our estimates from the common statistics of 800 undernourished and 2–3 billion malnourished people (FAO, IFAD, UNICEF, WFP, WHO 2022). Income poverty data was only available for subnational administrative units, resulting in border artefacts. Moreover, impact indicators poverty and inequality can be thematically linked to hotspot indicators. Since we analyse their spatial co-occurrence rather than causality or statistical correlation, collinearity between indicators should not affect our results.

Our results rely on the quality and accuracy of input data, which can vary across space. We use ERA5 climate data at 0.25° resolution, which may overestimate the spatial extent of extreme weather events. While higher-resolution climate products such as CHELSA-W5E5 can provide finer spatial detail, they also introduce new uncertainties, particularly for extreme indices (Karger *et al* 2023). A comparison of ERA5 with $1 \times 1$ km$^2$ DayMet data for North America showed broadly consistent spatial patterns (figure S12). Pixel-level correlations were modest ($r \approx 0.18$–$0.60$), with differences likely stemming from the use of local station data and terrain corrections for DayMet, thus reflecting methodological choices rather than the superiority of one dataset. Importantly, ERA5 has been validated against station data and captures large-scale variability and trends in extreme events reasonably well (Ahn *et al* 2024), corroborating its use for our multi-index, multi-region analysis.

The official definitions of Indigenous peoples and the legally recognised boundaries of their territories are often subjects of debate and contention (Garnett *et al* 2018). This can lead to disagreements and inconsistencies about the definitions of Indigenous peoples and potentially to the omission of areas with presence of Indigenous communities, in addition to the relatively coarse scale of the dataset and the limitations of publicly available geospatial datasets. Moreover, we could only use population level statistics, which likely miss individual effects and extreme cases of burdens in subpopulations. Our analysis uses static data providing a snapshot of current conditions, which restricts comparisons to global thresholds. This, however, would be relevant for future analysis investigating how burdens evolve over time.

The spatial extent of burden hotspots is conservative due to strict thresholds. A sensitivity analysis with more liberal thresholds shows increased spatial extents of burden hotspots and their co-occurrence, and consequently more people and agricultural area located in those hotspots, but conclusions remain robust (see figures S8 and S13). We further note that datasets used in our study (i.e. farm size and Indigenous lands) are only suitable for global-level analyses due to their relatively coarse resolution or lack of local specificity. Attempting to apply these datasets at the regional or even local level can lead to inaccurate conclusions and undermine the validity of findings. While this might limit the applicability of our results to local policymaking, they remain valuable for informing global policy on trade, tariffs, food security, or development expenditure. Our insights are hence intended to support regional prioritisation and global agenda-setting rather than direct local policy design, and can serve as a starting point for more detailed, context-specific research and policy development using localised data.

### 4.6. Implications

We provide a geographical assessment of hotspots of key agrifood-system burdens at subnational level, highlighting the diversity of agrifood-system burdens and that different world regions face different burden profiles. Moreover, we derive estimates of populations and agricultural areas located in regions of burden hotspots. These insights lead to key implications for future research in agrifood systems, as well as policy and decision making.

Burden hotspot regions represent priority regions for further investigation, particularly into factors explaining their occurrence as well as quantifying burden costs for social–ecological systems, for example through case study research in regions characterised by burden hotspots. Knowledge about the geographies of agrifood-system burdens as well as communities and regions facing the greatest burdens can assist regionalised, context-specific studies and research that can support decision-making, tailoring of policies, and the alleviation of these burdens in the future.

Regions facing burdens from poverty and/or malnutrition can require social protection measures, nutrition-specific interventions, or policies promoting food security and income stability (UNICEF 2023), while regions facing burdens from environmental footprint and weather extremes can require other measures, e.g. sustainable land management, climate-smart land-use practices, or improved supply chains (Fanzo and Miachon 2023). Even addressing tropical deforestation as a single contributor to the environmental footprint requires context-specific interventions (Seymour and Harris 2019). Addressing combined social–ecological burdens requires integrated, cross-sectoral approaches, for example through agroecological transitions to improve ecosystem functioning and food security (Ceddia *et al* 2024). More generally, removing barriers regarding agency, structure, and resource access for communities in policy is key for making agrifood-system more sustainable and just (Blesh *et al* 2023).

Solutions are urgent and required for agrifood-system transitions to produce healthy, affordable, and sufficient food while safeguarding vital ecosystems (Díaz *et al* 2018, FAO & IFAD 2020), especially given rising food insecurity, the cost-of-living crisis, and the exceedance of several Earth system boundaries (Moallemi *et al* 2024). Yet, silver bullet solutions will not be able to address global agrifood-system burdens. Spatially targeted and bundled solutions will be needed to maximise their impact if they address the intertwined nature of agrifood-system burdens (Barrett *et al* 2022), creating synergies for people and the environment. Successful examples include alleviating poverty and reducing climate change impacts (Wollburg *et al* 2023), reducing malnutrition and environmental impacts (Lopez Barrera and Hertel 2023), and reducing inequality and climate change impacts (Emmerling *et al* 2024).

Current agrifood-system assessments are limited by the restricted spatio-temporal and thematic coverage of data (Béné *et al* 2019), i.e. through inconsistent time series, missing recency of data, a lack of subnational data, and spatial data gaps for key agrifood-system indicators. Addressing these limitations regarding the availability of such indicators, in addition to expanding the set of indicators, should become a priority to further improve spatial detail, allow a more comprehensive representation of key burden dimensions, and enable monitoring changes in burden profiles. Our analysis presents a straightforward approach to identify hotspots of agrifood-system burdens based on spatial association. Establishing causal mechanisms of burden profiles (Biesbroek *et al* 2017) or identifying archetypical burden patterns (Oberlack *et al* 2019) can help to define and unravel interactions and feedbacks between burden dimensions, and to identify—similar to weather and climate events—compounding or cascading burden effects (Zscheischler *et al* 2020, Mehrabi *et al* 2022).

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: (Levers *et al* 2025) https://doi.org/10.5281/zenodo.15340862.

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## Conflict of interest

The authors declare no competing interests.

## Author contributions

C L: Conceptualisation, Funding acquisition, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualisation, Writing—original draft, Writing—review & editing. Z M: Conceptualisation, Data curation, Writing—review & editing. K B: Data curation, Writing—review & editing. N R: Conceptualisation, Resources, Supervision, Writing—review & editing. S S: Conceptualisation, Writing—review & editing. R S: Conceptualisation, Project administration, Resources, Supervision, Writing—review & editing.

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