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Crop harvests for direct food use insufficient to meet the UN's food security goal

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Rising competition for crop usage presents policy challenges exacerbated by poor understanding of where crops are harvested for various uses. Here we create high-resolution global maps showing where crops are harvested for seven broad use categories—food, feed, processing, export, industrial, seed and losses. Yields for food crops are low relative to other crop-use categories. It is unlikely, given current trends, that the minimum calorie requirement to eliminate projected food undernourishment by 2030 will be met through crops harvested for direct food consumption, although enough calories will be harvested across all usages. Sub-Saharan African nations will probably fall short of feeding their increased population and eliminating undernourishment in 2030, even if all harvested calories are used directly as food.

Competition for crops harvested for various uses has mounted in recent decades[1]. Crops used for animal feed, crop-based biofuels and other end uses can result in a smaller fraction of the same crop being available for direct human consumption as food. This competition also includes crop switching from those that are directly consumed as food to those that are not. In addition, rising demand for animal feed combined with inefficient feed conversion ratios ultimately mean reductions in calories left for human consumption[2,3], challenging the achievement of the United Nations' (UN's) Sustainable Development Goal (SDG) 2 of food security for all by 2030[4]. There are many dimensions of food insecurity, and merely increasing food production does not ensure food access, utilization and stability[5]. Yet, at present, there is widespread yield stagnation in major global food cereals[6,7], and a growing global middle class is increasing its demand for food products that rely on crops harvested for feed and processing[8]. Shifting uses and demands are also producing profound environmental and climate impacts through unsustainable resource use and the clearing of natural landscapes, raising questions about whether the trends in crop harvests, when not meant for direct food consumption, are aligned with the common interests of meeting the SDGs[9–11].

There is a current lack of detailed understanding of the patterns and trends of crops harvested for initial usage across the world. This has hampered the development of effective, locally relevant policies that balance global needs of food security and minimizing environmental impacts[12–15] through reconfigurations of cropping systems. Here we combine annual country-level information on seven uses of crop production[1] —food, feed, processing, export, industrial, seed and losses—over 50 years (1964–2013) with recently developed annual global gridded harvested areas and yields of ten major individual crops[16]. These ten major global crops—barley, cassava, maize, oil palm, rapeseed, rice, sorghum, soybean, sugar cane and wheat—account for ~83% of all harvested food calories[17] and ~63% of global harvested areas[18], a proportion that has remained stable for the past half century (between ~58% and 64%). Specifically in our analysis, a crop's grid cell-level harvested area is split (Methods and Supplementary Data 1) and combined with yields (tons ha^{-1} per year) to give seven uses of crop production (tons per year). Using the crop-specific calorie, protein and fat contents (which can vary widely among crops), we estimate the total grid cell-level calories, protein and fat production and nutritional yields for the seven utilization categories.

Results

Growth in harvests of crops meant for exports, processing and industrial use, together with their higher yields and faster yield gains, stands out globally; at a more granular level, this was driven by specific global regions that are getting increasingly specialized in harvesting crops for these usages.

Changes in global-level harvested areas. At the global scale, we find that crops harvested for direct food utilization have the highest area and have been relatively stable over the study period (Fig. 1a). However, as the total harvested hectares have increased globally (Supplementary Table 1), this has translated into decreasing fractions of crops harvested for direct food utilization, from ~51% in the 1960s (average over 1964 to 1968) to ~37% in the 2010s (average over 2009 to 2013), with a similar reduction in feed crop harvests (Table 1). Conversely, there has been a substantial increase in crops for processing, exports and industrial use (Fig. 1a, Table 1 and Supplementary Table 1). The increase in industrial crop harvests occurred after year 2000. Around the same time, harvested hectares for exported crops ramped up and by the 2010s had surpassed those of crops harvested for feed use (Fig. 1a). Crops harvested for seed usage and losses are relatively minor, and we will not discuss them further. If the global trends observed in the past 20 years continue (Fig. 1a), by 2030, crops harvested for exports, processing and industrial use will account for ~ 23%, 17% and 8% of overall harvested hectares, whereas those for food will decrease to ~29% (Table 1).

Changes in global-level crop yields. We find that crops harvested for direct food usage generally have had lower yields than all other sectors at the global scale over the time period of the study (Fig. 1b–d). This is not a new phenomenon, as crops harvested for

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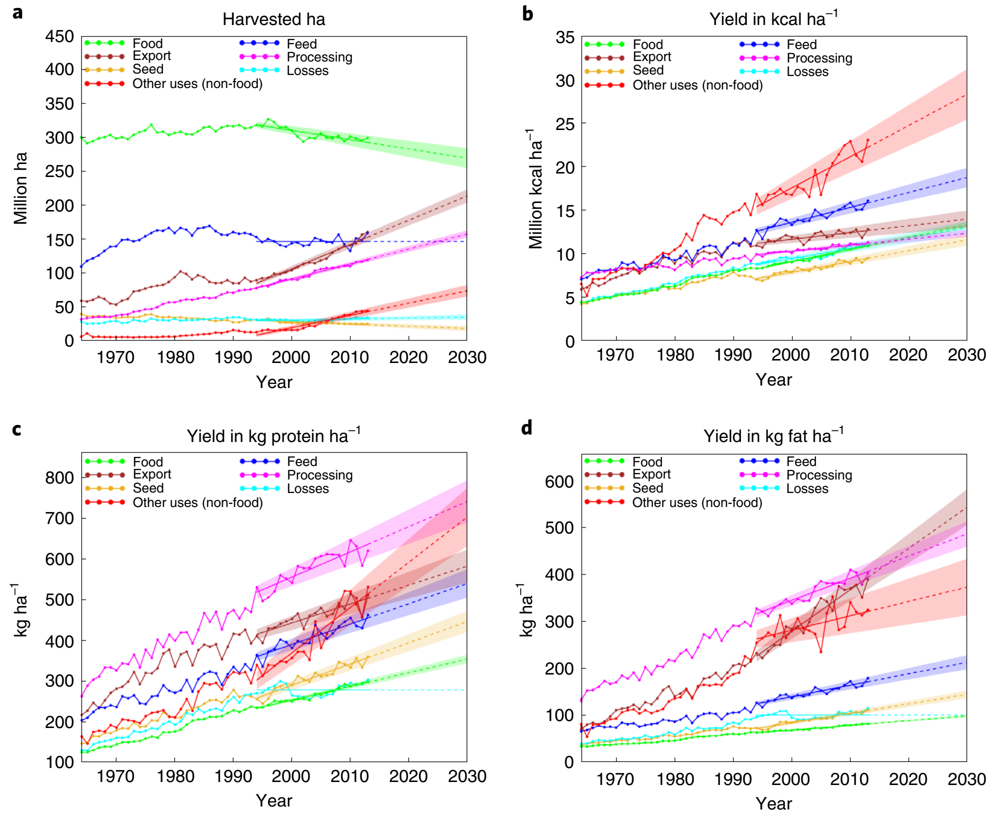

Fig. 1 | Sector-based global crop-utilization trends. a–d, Observed total harvested ha (**a**), average yield in kcal ha^{-1} per year (**b**), average yield in protein ha^{-1} per year (**c**) and average yield in fat ha^{-1} per year (**d**) in the seven sectors of food, feed, processing, export, other uses (non-food/industrial), seed and losses from 1964 to 2013, annually, and projections to 2030 based on the past 20 years. The shading shows the 90% confidence interval for the significant linear model projections.

direct food utilization have always had lower yields relative to other sectors (Supplementary Table 1). What has changed, however, is the ramping up (steeper positive slopes) of industrial, export and processing crop yields (Fig. 1b–d and Table 1). At these rates, caloric yields of industrial-use crops could increase by 28% from the 2010s to 2030 compared with 24% and 21% yield increases of crops harvested for directly consumed food and for feed use (Fig. 1b). Given that caloric yields of industrial-use crops are already substantially higher than food and feed crops (2× and 1.4×, respectively, in the 2010s), the faster caloric yield increases for industrial-use crops will widen this gap (2.1× and 1.5×, respectively). Yield measurements in other units of protein and fat show similar results (Table 1, Fig. 1c,d and Supplementary Table 1).

Changes in the spatial patterns of harvested areas and production. Within country-level information on harvested areas and productivity based on utilization categories is required for developing more locally effective agricultural policies. Over the course of the study time period 1964 to 2013 (Fig. 2a,b and Supplementary Video 1), we find changes in all continents when spatially analysed at the grid-cell level, except for most parts of Africa. Even in Africa, there are locations with fractional reductions in food crop harvests over the study period, such as parts of Angola, Ghana, Nigeria and South Africa. Within these and other countries, the exact location, magnitude and direction of the change varies from one region to the next (that is, compare Fig. 2a with Fig. 2b).

Crops harvested for direct food utilization have been prevalent in Asia, though much has changed since the 1960s (Fig. 2a,b and Supplementary Video 1). In China, there appears to be an imaginary belt, north and west of which harvests of crops used as directly consumed food decreased between the 1960s (Fig. 2a) and 2010s (Fig. 2b), while those for other uses increased. This belt appears to roughly extend from the northern half of Jiangsu (a province on the Yellow Sea in the east), curving westwards and southwards through northern Anhui, southern Henan, central Hubei and the northern tip of Hunan, and then turning sharply south and splitting Guangdong (a province on the South China Sea) through the middle. The sector gaining from the 10–20% fractional food harvest reduction varies. The increase in crops for feed, processing and industrial usage increases as one moves northward, especially north of Jiangsu and Anhui (Fig. 2a,b and Supplementary Video 1).

Similarly, in India, there is a north–south zone encompassing eastern Haryana in the north, moving southwards through eastern Rajasthan, western Madhya Pradesh to eastern Maharashtra in the south, where there was a drastic reduction in crops harvested for direct food utilization over the study period (Fig. 2 and Supplementary Video 1); crops harvested for processing primarily increased. Changes in South and Southeast Asia over the study period are primarily away from once-dominant harvests of directly consumed food crops to feed crops, followed by processing crops, export crops and industrial-use crops, as in Myanmar and Thailand. In Malaysia, the growth was in export and industrial-usage crops, whereas in Indonesia, it was export crops and smaller increases in industrial-utilization crops. Central Asian states, especially Kazakhstan and some parts of Russia, witnessed a large reduction in crops harvested for direct food use over the study period, replaced by the crops destined for exports between the two periods (Fig. 2 and Supplementary Video 1).

Table 1 | Sector-based global crop-utilization changes

	Harvested area (ha)		Harvested production (kcal)		Harvested production (protein)		Harvested production (fat)	
	Percentage harvested in 1960s, 2010s, 2030 (of seven-sector total; %)	Current rate of change (in million ha per year) ± standard error	Percentage production in 1960s, 2010s, 2030 (of seven-sector total; %)	Current rate of change (in million kcal ha^{-1} per year) ± standard error	Percentage production in 1960s, 2010s, 2030 (of seven-sector total; %)	Current rate of change (in kg protein ha^{-1} per year) ± standard error	Percentage production in 1960s, 2010s, 2030 (of seven-sector total; %)	Current rate of change (in kg fat ha^{-1} per year) ± standard error
Food	51, 37, 29	$-1.36 \pm 0.23^{***}$	42, 32, 26	$0.14 \pm 0.01^{***}$	38, 26, 20	$3.35 \pm 0.17^{***}$	32, 14, 9	$1.00 \pm 0.04^{***}$
Feed	21, 18, 16	0.17 ± 0.25^{ns}	28, 23, 20	$0.17 \pm 0.02^{***}$	27, 20, 16	$4.99 \pm 0.56^{***}$	27, 15, 11	$2.44 \pm 0.24^{***}$
Processing	6, 14, 17	$2.21 \pm 0.08^{***}$	8, 13, 14	$0.07 \pm 0.01^{***}$	10, 21, 24	$6.19 \pm 0.83^{***}$	16, 27, 27	$4.71 \pm 0.43^{***}$
Export	10, 18, 23	$3.58 \pm 0.16^{***}$	12, 18, 21	$0.08 \pm 0.02^{***}$	14, 22, 26	$4.65 \pm 0.65^{***}$	15, 33, 41	$8.80 \pm 0.61^{***}$
Others (industrial)	1, 5, 8	$1.82 \pm 0.13^{***}$	1, 9, 15	$0.36 \pm 0.05^{***}$	1, 6, 11	$11.13 \pm 1.14^{***}$	2, 8, 10	$3.06 \pm 0.96^{**}$
Seed	6, 3, 2	$-0.34 \pm 0.06^{***}$	5, 2, 2	$0.12 \pm 0.01^{***}$	6, 3, 2	$5.22 \pm 0.42^{***}$	5, 2, 1	$2.02 \pm 0.13^{***}$
Losses	5, 4, 4	$0.15 \pm 0.07^{*}$	4, 4, 3	$0.12 \pm 0.01^{***}$	4, 3, 2	0.80 ± 0.57^{ns}	4, 2, 1	0.46 ± 0.26^{ns}

ns, $P > 0.05$; $^{*}P \leq 0.05$; $^{**}P \leq 0.01$; $^{***}P \leq 0.001$; Others = industrial-use crops; rate of change based on observations for 20 years: 1994–2013

In Australia in the 1960s, food crops were harvested everywhere, accounting for ~10% of the total, which declined to ~5% by the 2010s. This was accompanied by small reductions in crops harvested for feed and export and balanced mainly by increases in crops for processing and industrial utilization (Fig. 2 and Supplementary Video 1).

In Europe in the 1960s, crops were dominantly harvested for food and feed, but by the 2010s, this changed to include crops harvested for processing (Fig. 2 and Supplementary Video 1). In France, major reductions in feed crops have been balanced by growth in processing, export and industrial-use crops. In Spain, the primary change is from crops harvested for direct food to those of feed. In Germany, crops harvested for export have replaced those for direct food utilization.

Latin America used to dominantly harvest food crops (as in Mexico) or food and feed crops (as in Brazil and Argentina) (Fig. 2 and Supplementary Video 1). Midwestern Brazil used to harvest only food crops, and feed and processing crop harvests were restricted to the Atlantic states (the 1960s; Fig. 2a), but by the 2010s (Fig. 2b), harvests of food crops had become a negligible fraction in Midwestern Brazil (as in Mato Grosso), and crops harvested for processing and exports are dominant now. In the Atlantic states of Brazil, one of the major changes is the increased proportion of harvests for industrial crops. In Argentina, over the study period, the proportion of crops harvested for food and feed has decreased, and this utilization has been mainly replaced by crops harvested for processing; crops harvested for exports changed, but the direction of change was spatially heterogeneous across Argentina (Fig. 2 and Supplementary Video 1). In Mexico, the primary change is the reduction in the fraction of crops harvested for direct food consumption and the increased harvests of crops for feed.

Crops harvested for food and feed are also on the decline proportionally in North America. The United States has experienced a change from the dominance of food and feed crops in the 1960s to processing and industrial-usage crops in the 2010s. Detailed changes in the United States and Canada vary from one location to the next (Fig. 2), though the major change is the lower fraction of crops harvested for direct food consumption.

Results are similar when viewed through the lens of calories, protein and fat with local-level differences as yields vary based on the measurement units (Supplementary Fig. 1). Further dramatic changes can be expected if observed linear trends from 1994 to 2013 at each grid cell continued until 2030 (Supplementary Fig. 2).

Calories harvested in 2030 and achieving UN SDG 2. We compare the extra food calories that will potentially be harvested in 2030 (Fig. 3a and Supplementary Data 2) to those required for both the projected extra population and feeding the projected undernourished population in each country (Fig. 3b and Supplementary Data 2). As an extreme case, we also compared whether total calories (all seven utilization sectors) would be sufficient (Fig. 3c and Supplementary Data 2). Altogether, we evaluated 156 countries, of which 86 had reported undernourished populations (Supplementary Data 2). On the basis of the minimum dietary energy requirement (MDER), we find that countries with reported undernourished populations will have a shortfall of ~675.4 trillion kcal per year to nourish the increased population and the expected undernourished from their extra harvested food calories. However, compared with the more realistic average dietary energy requirement (ADER), this shortfall will be ~993.9 trillion kcal per year (or ~70% from requirements) in 2030 (15 additional scenarios of undernourished populations in 2030 (provided in Supplementary Data 3) show global calorie shortfalls may similarly range from ~587.2 trillion kcal per year to ~1,269.3 trillion kcal per year based on the MDER level of nutrition requirement, and ~880.7 trillion kcal per year to ~1,755.6 trillion kcal per year based on the more realistic ADER level of nutrition requirement in 2030).

Countries reporting undernourishment can, however, meet their requirement of extra calories in 2030 for both population change and those for the undernourished if calories from other utilization sectors are diverted and consumed directly as food calories (Fig. 3c and Supplementary Data 2 and 3). Though at the global scale, it appears that countries with high levels of undernourishment in 2030 can divert just a portion of their total harvested calories and meet some of the requirements of UN's SDG 2 (ref. [4]). In reality, many of the individual countries concentrated in sub-Saharan Africa have limited scope of diversion of calories from other sectors such as feed, processing or exports as crops for direct food use, as they already harvest most crops for direct food consumption (Fig. 2 and Supplementary Figs. 1 and 2). As such, many countries in this region may see deepening reliance on food imports. Note that the UN's second SDG goal is broader in scope, including efforts to end malnutrition and increase agricultural productivity, among other goals[4]. Reconfiguration planning[19] can use our spatially detailed information (Figs. 2 and 3, Supplementary Figs. 1 and 2 and Supplementary Data 2 and 3) in conjunction with policies that incentivize increased food crop harvests globally and ensure their equitable distribution to undernourished regions when local a

b

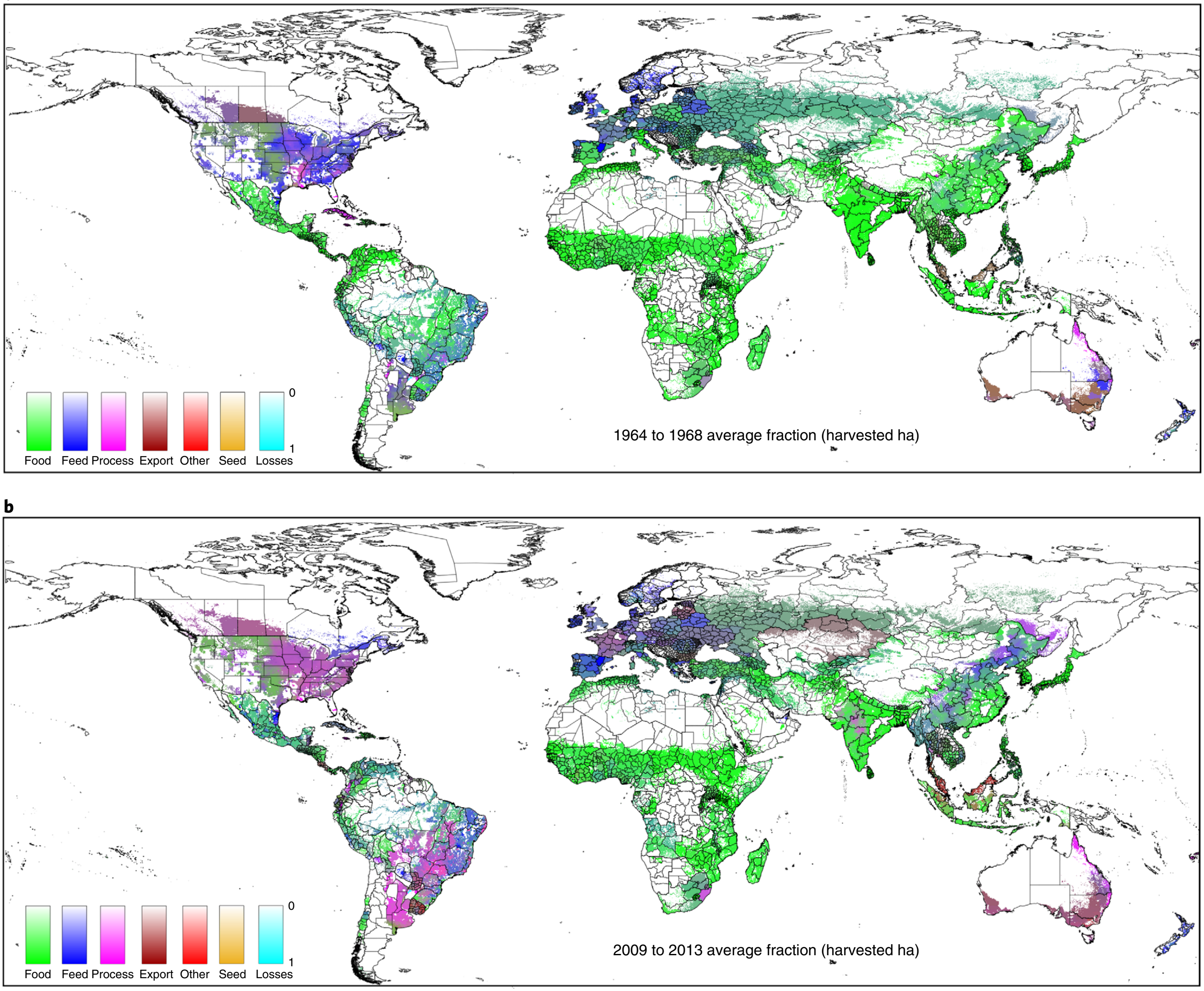

Fig. 2 | Sector-based spatial changes in crop harvests. a,b, The fraction of a grid cell in one of seven categories—food, feed, processing, export, other (non-food/industrial use), seed and losses—in each period, 1964–1968 (**a**) and 2009–2013 (**b**).

production is not sufficient[20,21]. This will require supply chain management[22,23] and detailed analysis of optimization scenarios[24] with our maps and tables as an important step linking specific production regions with the initial use of that production.

Discussion and conclusion

Spatially, the shift in the harvested area from food and feed towards processing in the United States is reflective of the evolving role of the country in global crop production and renewable energy targets[25]. Similar but less dramatic changes have occurred in Europe. The changes observed in Latin America from a region oriented to food production, to harvesting feed and processing crops, have been observed since the late 1990s with the expansion of maize and soybean harvests pushed by commodity prices and exchange rate[26] and at the cost of tropical ecosystems[27–30]. China's movement away from harvesting crops for direct food utilization to processing and feed crops has been mainly driven by the changes in its consumption structure due to rising incomes and population where people demand high-value food products[31]. The country can substantially improve its domestic soybean (and other crops) production by optimizing the spatial distribution (Fig. 2 and Supplementary Figs. 1 and 2) and thus reducing pressure on domestic and foreign environmental resources. Similarly, in India, demand for processed food has increased due to demographic changes and health consciousness, increased demand for branded and convenient items, modernization of retail and food service sectors and heightened efforts to develop food manufacturing by the government[31].

Though a lack of other micronutrients such as vitamin A, iron and zinc can produce a suite of deficiency diseases[3,32,33], here we restrict ourselves to macronutrient production for their initial utilization. After the initial intended utilization, there could also be a flow between utilizations, the easiest of which to understand is crops harvested for exports turning up in any utilization category within importing nations (including re-exported), a more complicated problem of global flows between nations and categories[34] that should be explored in subsequent investigations. The sector-specific crop-utilization information at the time of crop harvests that we present are estimates and built using gridded crop[16] and the Food and Agriculture Organization of the UN Food Balance Sheet (FAO FBS)[1] data annually for 50 years from 1964 to 2013; post-2013

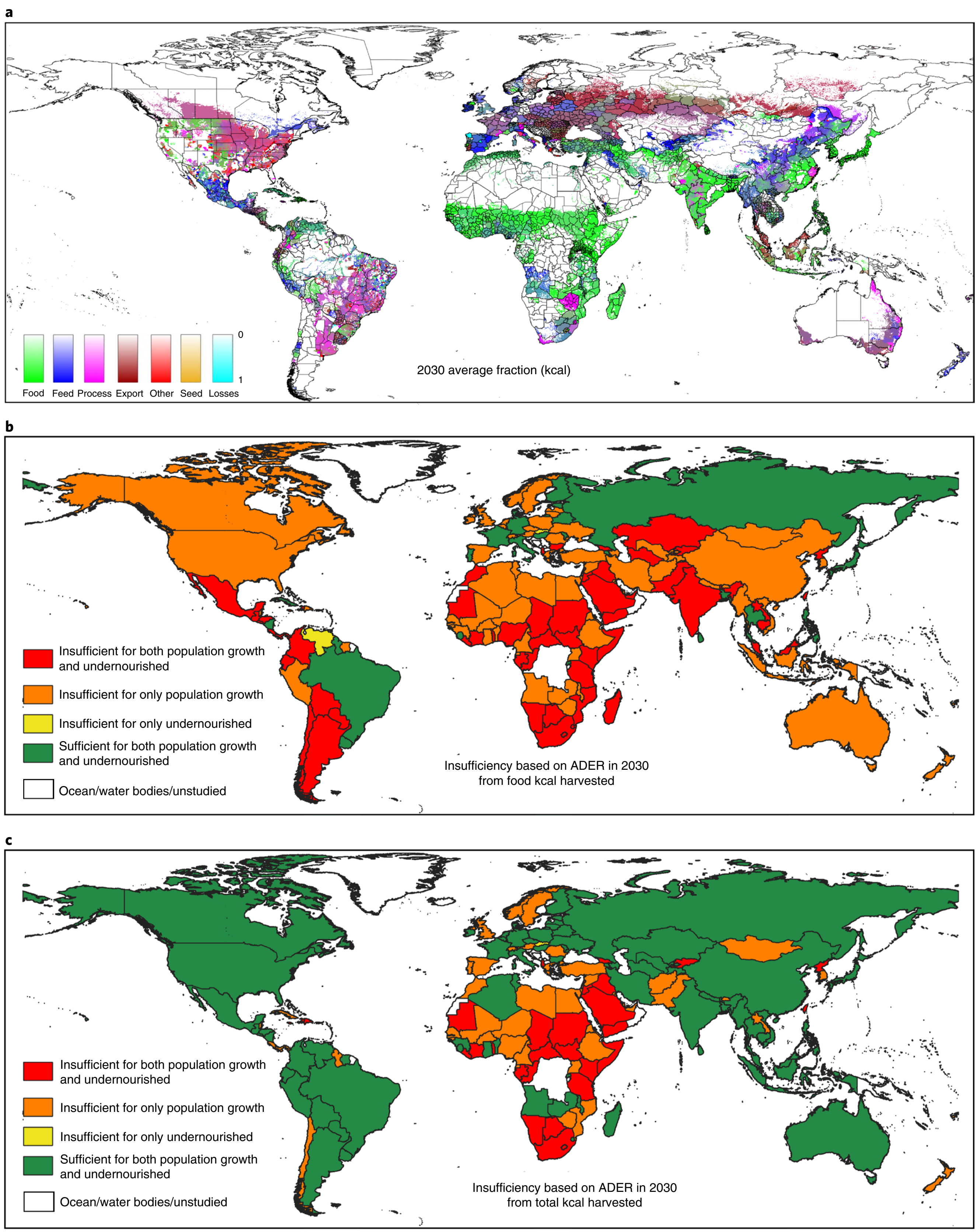

Fig. 3 | Meeting UN SDG goal 2 in 2030. **a**, Same as Fig. 2 but for the projected kcal ha^{-1} per year in 2030 per utilization sector and then mapping the fraction of total kcal ha^{-1} per year projected as harvested. **b**, Shortfall or gap from kcal per year harvested in 2030 as crops for direct food use and those to plug the gap from population growth and/or undernourished population. Computed based on the 2018 to 2020 ADER number for the country. **c**, Same as **b** but the kcal per year harvested used for computation is the total across all the seven sectors and shortfall is from whether the total calories harvested were used for direct food consumption (little to no processing).

FAO FBS data uses a different methodology (detailed sources of uncertainty are provided in Methods). Nevertheless, our analysis provides new insights into the shifting patterns of crop utilization within nations and has important implications for the sustainability of natural resource use and the fraction of resource use that directly supports food security and nutrition.

We find that over roughly 50 years, the growth in global crop harvests (total harvested hectares have increased 28%) favoured exports, industrial- and processing-use crops. In specific areas of the world, this change has accompanied reductions in food and feed crop harvests. We also find low food crop yields and the potential for industrial crop yields to become more than twice those of food crops and 1.5 times those of feed crops by 2030. Much of the non-direct food harvest regions are in food-secure or wealthy nations outside of sub-Saharan Africa and Asia, which does not increase undernourishment in these regions from production constraints. However, changes are underway even in food-insecure regions. We find that out of the 86 countries with undernourished populations studied (see Methods for countries not studied yet likely to have undernourished population), 31 countries will probably not meet their caloric requirements in 2030 for the undernourished and the increased population, even when all harvested calories were diverted and used as food calories (Fig. 3c); another 17 countries will probably not meet the caloric requirement of their expected extra population in 2030, raising the question how will they then feed their undernourished population (Fig. 3c). We recommend that food-insecure nations, non-governmental organizations and other aid groups immediately incentivize harvests and yield growth of directly consumed food crops. To close any gap in nourishment in food-insecure nations that cannot be locally met, highly productive world regions should also be incentivized to divert a portion of their production towards directly consumed food crops. Such changes should prioritize equitable access for the food undernourished and ensure justice for farmers and agriculture-sector livelihoods and should be substantively discussed during policymaking.

Methods

Crop-utilization maps. Annual global crop-utilization maps were developed from fusing national-level fractional crop-utilization information and gridded crop maps. Fractional crop-utilization data were built using the FAO FBS (old methodology data that extends from 1961 to 2013)[1]. We first compute the total utilization of food, feed, processed, export, industrial, seed and loss per crop in each country and for each year and then compute the fractional utilization (Supplementary Data 1). In other words, the same crop can have seven different utilizations that vary each year. For each of these ten crop product groups in the FAO FBS[1]—(1) barley and products, (2) cassava and products, (3) maize and products, (4) palm oil plus palm kernel oil, (5) rape and mustard seed, (6) rice and products, (7) sorghum and products, (8) soyabeans, (9) sugar cane and (10) wheat and products—the utilization is reported in thousands of tons. The annual (seven) fractions of these ten product groups are fused respectively to (1) barley, (2) cassava, (3) maize, (4) oil palm, (5) rapeseed, (6) rice, (7) sorghum, (8) soybean, (9) sugar cane and (10) wheat annual gridded crop data. The gridded crop data are an updated version of crop-specific harvested areas and yields at 5 min spatial resolution[16]. The national-level crop-utilization fraction information is used to split a crop's grid cell-level total harvested area into the seven constituent categories and additionally using the yield information together with the calorie, protein and fat content of a crop (Supplementary Table 2), the production in these three units and for the seven utilization categories for the crop determined. The process is repeated for all ten crops (annually for each nation; rarely, a nation harvests all ten crops, for example, China). Thus at the grid-cell level, we get the total harvested areas and total production (in units of kcal, kg protein and kg fat) per country and each year for each of the seven sectors. From these two pieces of information, yield can be computed. Not only do the utilization fractions change with time, but also the location and amount of the individual crop harvest, leading to a pattern developing of where crops are harvested for seven different utilizations. There are multiple sources of uncertainty: (1) we used only the top ten global crops in this study due to the limitation on temporally varying high-resolution gridded crop data to just ten crops; if the information of additional crops is added, the accuracy will increase. (2) We applied the computed national-level crop fractional utilization at subnational scales. At present, there is no globally available information on subnational-level crop utilization across nations (either due to privacy concerns or record-keeping was not possible). It is unlikely that such information will ever become available globally. Map accuracy can subjectively improve if country experts provide judgements on subnational crop utilization. Broadly, however, the utilizations agree with expected patterns in major countries such as the United States and Brazil. Further, food crop harvests are concentrated in the low-income country that may partly explain lower food crop yields at the global scale. (3) The sum of the total of the seven types of crop utilization: food, feed, processing, export, industrial, seed and losses within a country is equated to the within-country annual crop production after adjusting with imports and stock changes. Equating the seven-sector total crop utilization to this adjusted crop production assumes identical proportional contribution to the seven sectors of crop utilization, from crop production, imports and stock changes. Distortions in the maps are then likely in import-dependent nations, but such nations also have less within-country crop production (often zero), reducing mapping errors (stock changes ~ zero in the long term). (4) There is uncertainty in both the FAO and the gridded crop data. (5) For conversion of production to kcal, kg protein and kg fat, we used a static conversion factor globally (Supplementary Table 2). (6) Countries with dominant crops other than the top ten global crops will have larger map errors. (7) Exported crops are variously used within importing nations, but if an imported crop gets re-exported by the importing nation, it creates map errors.

Trends, changes and projections. For global-scale yield computation shown in Fig. 1, we used the total grid cell-level harvested hectares and production information in calories, protein and fat per sector and summarized across all grid cells with long-term data globally. The utilization sector-specific yield was then the ratio of the total global production and the total global hectares harvested in that sector. When the production was measured in kcal, the yield was in units of kcal ha^{-1} per year, and in a similar way, when in units of kg protein and kg fat harvested, the yield was in units of kg protein ha^{-1} per year and kg fat ha^{-1} per year, respectively.

We used the past 20 years' data (1994 to 2013) and fitted a linear model for projection. We tested the significance of the model's slope using a two-sided t-test at the 5% significance level. We also tested for normality in the residuals and white noise error. We conducted Lilliefor's two-sided test of the NULL hypothesis for normality conditions that the residuals were normally distributed against the alternative at the 5% level (rejection of the NULL indicates a non-normal distribution of the residuals). For white noise error in the residuals, we conducted the Ljung–Box Q test for residual autocorrelation (NULL hypothesis: there is no autocorrelation in the residual; rejection of the NULL at the 5% level indicates autocorrelation). Rarely were the conditions violated (Supplementary Table 3). Non-normal residuals and autocorrelation in residuals are indicative of a lack of a good fit. In that case, an alternate model can be explored. The actual slope and its significance level are given in Table 1. When the t-test was not significant, we assumed an intercept-only model (for example, feed harvested ha trend in panel a—R^2 is only 0.03 for a linear model in this case; Supplementary Table 3). Models thus selected were projected out linearly to the year 2030. Nonlinearity in the model parameters is a major challenge, and while using higher-order terms can lead to better model fits, they can also lead to acceleration due to higher-order terms and unreliable extrapolations. The linear projection is a prescribed scenario and, further, it is based on current locations of a crop that may change in the projected period. Yield growth rates could also be changed due to climate change[16,35,36] affecting the results of the study. We restricted to using the 1994 to 2013 data as the gridded data, and the FAO FBS data ends in 2013. Though more recent FBS data are now available, they are built using a different methodology and are for only a few years. As such, they do not allow for the merging of the two FBS datasets. Construction of the gridded data also lags as they are built based on local surveys of agricultural production that have delayed reporting, and the gridded data that we used represents the most up-to-date high-resolution time-series data on a wide range of global crops. For example, for two similar (but not time series) gridded crop data (MapSPAM (https://www.mapspam.info/) and GAEZ (https://gaez.fao.org/pages/theme-details-theme-5)), the latest year of gridded crop data is circa 2010.

To plot Fig. 2, we first determined the average harvested hectares in each period/panel (1964 to 1968, 2009 to 2013) in each of the seven categories for all crops per grid cell. Then we determined the total, across all utilizations, and then the fraction of the total in each category (0–1) per grid cell. Each category is coloured in a solid colour with intensity ranging from 0% opaque (at 0 fraction) to 100% opaque (at 1 fraction). For example, the food category is in green and the export category is in brown colour. All seven categories are overlaid in the same sequence as the legend. The same process in colour coding was used in Fig. 3a and Supplementary Figs. 1 and 2.

Calories and population projections. The number of global undernourished people (2014–2016 to 2018–2020 average) reported by the FAO[37] was 633.98 million. We assume that in 2030, the number of the undernourished will be 656.8 million, as projected in the latest FAO report on the state of global food security[38]. In this report, country-specific undernourished numbers for 2030 are not available. To understand the requirement of calories to overcome undernourishment and population change in 2030 per country, we scale each country's current number of undernourished population with 656.8/633.98. Scaling thus assumes that all undernourished countries will make the same identical progress between now and 2030, which is a scenario.

We explored 15 other potential scenarios using three different periods of country-wise undernourished information: (1) the entire undernourished population (19 years; 2000–2002 to 2018–2020); (2) ten years before and including the latest year (2009–2011 to 2018–2020); and (3) five years before and including the latest year (2014–2016 to 2018–2020). First, we note that undernourished population numbers have high inter-annual variability and thus are not easy to model. Sometimes the entire 19-year data appear visually erratic, while at other times only sections of the data, such as the latest ten years or the latest five years of data, appear erratic. We fit the observed undernourished data as linear trends and project the (linear) trends forward to 2030. When the linear fit is not significant at the $P = 0.05$ level, we default to the 2014–2016 to 2018–2020 average undernourished population in the country. We studied more scenarios using the past five years of the observations as we felt that it was more likely that recent progress will continue. However, fitting with fewer data points also resulted in fewer significant linear model fits. We find that at the lower limit, the shortfall in calories in undernourished countries as ~587.2 trillion kcal per year based on the MDER level of nutrition requirement in 2030 and ~880.7 trillion kcal per year based on the more realistic ADER level of nutrition requirement in 2030 (Supplementary Data 3). On the higher end, the numbers were ~1,269.3 and ~1,755.6 trillion kcal per year shortfall based on the MDER and ADER level of nutrition requirement in 2030 (Supplementary Data 3).

Reducing crop yield gaps[39–41] is one of many ways to reduce the undernourished population (others include better access to food, reducing civil strife[42] and climate change impact planning based on predictions[35,36]). While there are many studies on the existence and closing of yield gaps, we do not explore them here and instead directly deal with the scenarios of reducing the undernourished population (that may stem from closing yield gaps among many other levers that control undernourishment). Of particular use would be studies that measure the change in yield gaps over time, because yield gaps are a dynamic function of both the production at the location in question and the ceiling against which it's being compared. Yield gap studies that compare against static ceilings miss an important component of these trends.

Note that even though we queried the FAO database for all the countries for undernourished population, several potential current countries with undernourished populations, such as Equatorial Guinea, Eritrea, Niger, Uganda, Zambia and Zimbabwe, were not returned from our search. Because we scale each country by global ratios, these countries are implicitly included but could not be reported at the individual country level. Thus our global-scale totals in Supplementary Data 2 for the calories required for the undernourished in 2030 is an underestimate, and in Fig. 3b,c, such countries are not reported as having a shortfall in calories for the undernourished. Generally, these countries are unable to harvest enough calories to feed their increased population and thus it is very likely that they will be unable to meet the demand of undernourished, but we do not have the undernourished numbers to project for 2030. We used the latest MDER and ADER values (year 2020) as those for 2030 (MDER and ADER values do not change much, and in most countries, we did not find trends that could be expressed simply, making any projection unreliable).

Data availability

The FAO FBS and crop data are from sources given in citations 1 and 16, respectively. The datasets generated in the current study (data in Figs. 1–3) are posted online at https://github.com/drayumn/IonE_UN_SDG and are also available directly from the corresponding author.

Code availability

All codes were developed in the Matlab programming language and are available upon request from the corresponding author. The global maps were plotted using QGIS.

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Author contributions
D.K.R. led the effort to design, conduct, analyse and write this report. L.L.S., A.S.G., K.F.D., T.A. and W.X. commented on and helped in interpreting the findings and contributed to the writing. D.K.R., L.L.S. and A.S.G. had discussed other versions of this work.

Competing interests
The authors declare no competing interests.

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