

# Increasing homogeneity in global food supplies and the implications for food security

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**The narrowing of diversity in crop species contributing to the world's food supplies has been considered a potential threat to food security. However, changes in this diversity have not been quantified globally. We assess trends over the past 50 y in the richness, abundance, and composition of crop species in national food supplies worldwide. Over this period, national per capita food supplies expanded in total quantities of food calories, protein, fat, and weight, with increased proportions of those quantities sourcing from energy-dense foods. At the same time the number of measured crop commodities contributing to national food supplies increased, the relative contribution of these commodities within these supplies became more even, and the dominance of the most significant commodities decreased. As a consequence, national food supplies worldwide became more similar in composition, correlated particularly with an increased supply of a number of globally important cereal and oil crops, and a decline of other cereal, oil, and starchy root species. The increase in homogeneity worldwide portends the establishment of a global standard food supply, which is relatively species-rich in regard to measured crops at the national level, but species-poor globally. These changes in food supplies heighten interdependence among countries in regard to availability and access to these food sources and the genetic resources supporting their production, and give further urgency to nutrition development priorities aimed at bolstering food security.**

crop diversity | plant genetic resources | agricultural development | global analysis

A shared axiom of ecology and nutrition is that, within certain ranges, diversity enhances the health and function of complex biological systems. Species diversity has been shown to stimulate productivity, stability, ecosystem services, and resilience in natural (1–5) and in agricultural ecosystems (6–13). Likewise, variation in food species contributing to diet has been associated with nutritional adequacy (14–17) and food security (18).

The development of sedentary agricultural societies and further rise of modern agriculture is generally considered to have led to a decline in the total number of plant species upon which humans depend for food (19, 20), particularly the wild, semi-domesticated, and cultivated vegetables and fruits, spices, and other food plants that supplemented staple crops with the provision of micronutrients and that bolstered food security historically during crop failures (21). Harlan (20) warned that

most of the food for mankind comes from a small number of crops and the total number is decreasing steadily. In the United States in the past 40 years, many vegetables and fruits have disappeared from the diet, and the trend is going on all over the world. More and more people will be fed by fewer and fewer crops.

More recent analyses of dietary transition in developing countries in association with globalization have noted increases in the diversity of plants contributing to diets locally, along with

a Westernization transition in preference of energy-dense foods (i.e., animal products, plant oils, and sugars) over cereals, pulses, and vegetables, and of particular major crop plants within these food categories over traditional crops (22, 23). The impact of such changes on overall crop diversity worldwide has not been comprehensively documented, although recent changes in varietal and allelic level diversity of some crops have been investigated (24–26). Given the potential food security implications of narrowing of the diversity of crop species both in production systems and in food supplies, an assessment of the global state of crop plant species diversity is warranted.

Here we examine changes in the diversity of the portfolio of crop species upon which humans primarily depend for food security in regard to calories, protein, fat, and food weight. Using national per capita food supply data published by the Food and Agriculture Organization (FAO) of the United Nations, we analyzed trends in the richness, abundance, and composition of measured crop commodities in the food supplies of 152 countries comprising 98% of the world's population from 1961 to 2009.

## Results

As a global trend, national per capita food supplies from both plant and animal sources consistently increased over the past 50 y for all variables, with animal foods becoming increasingly important in contribution to protein and oil crops dominating fat food supplies (Fig. S1).

## Significance

**This study provides evidence of change in the relative importance of different crop plants in national food supplies worldwide over the past 50 years. Within a global trend of increased overall quantities of food calories, protein, fat, and weight, and increased proportions of those quantities sourcing from energy-dense foods, national food supplies diversified in regard to contributing measured crop commodities. As a consequence, national food supplies globally have become increasingly similar in composition, based upon a suite of truly global crop plants. The growth in reliance worldwide on these crops heightens interdependence among countries in their food supplies, plant genetic resources, and nutritional priorities.**

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From 1961 to 2009, all 52 measured crop commodities, which included both individual crops and groups of crops producing similar products, with the exception of cottonseed oil, increased in geographic spread (i.e., were counted as contributing to food supply in an increasing number of countries; Fig. 1A and Fig. S2). The major cereals wheat, rice, maize, and barley, along with sugar, potatoes, and the general vegetables and fruits commodities maintained their ubiquity in food supplies across the planet over the past 50 y. Crop commodities with the greatest relative changes in spread over this period included oil crops such as soybean, sunflower, palm oil, and rape and mustard. Commodities showing relatively small changes in spread and not already globally ubiquitous included minor cereals such as millets, sorghum, and rye, and starchy root crops such as yams, cassava, and sweet potatoes.

Wheat, rice, maize, and other ubiquitous crop commodities were among those with the greatest gains in both relative and absolute abundance in national per capita food supplies over the past 50 y (Fig. 1B and Figs. S3 and S4). In addition, the degree of increase in spread was generally a good predictor of change in the abundance of the crop commodities in food supplies. For example, oil commodities such as soybean, sunflower, palm oil, and rape and mustard were among the crops showing the greatest average increase in relative abundance in national food supplies, whereas millets, rye, sorghum, yams, cassava, and sweet potatoes showed the largest declines. Such global changes in abundance of measured crops in national food supplies are similarly evident in global aggregated per capita food supply data, which assesses global quantities in relation to total world population (Fig. S4).

The richness of national per capita food supplies in regard to the 52 measured crop commodities increased consistently over the past 50 y for all variables (Fig. 2A and B and Fig. S5). National food supplies also increased slightly in evenness, indicating greater equality in the relative abundance of each of the crop commodities contributing to per capita food supply within each country, although mixed trends were evident worldwide (Fig. 2C and D and Fig. S6). Dominance (estimated as the proportion of a country's per capita food supply comprised of the most abundant crop commodity) declined as a global trend over the study

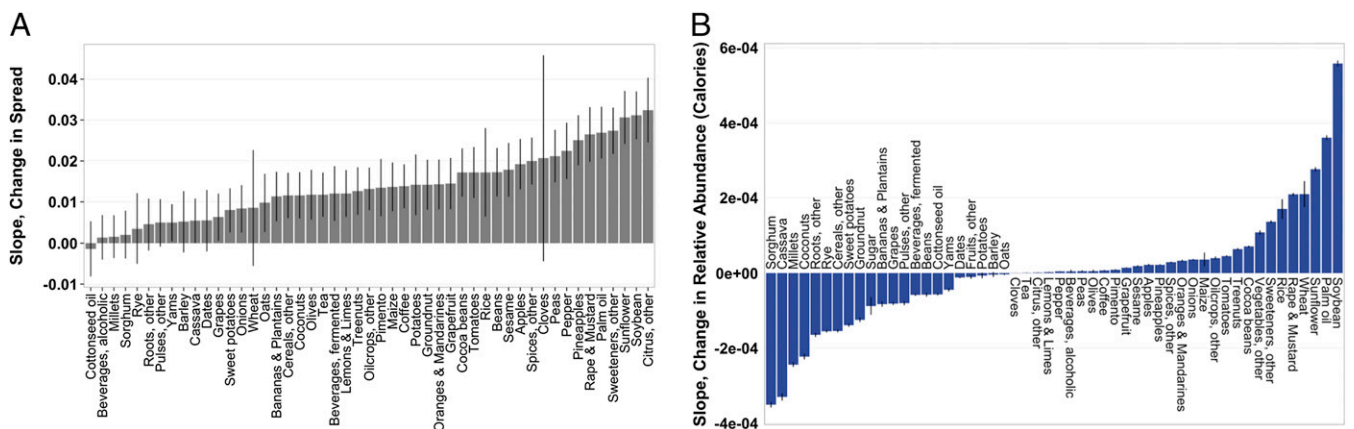
period (Fig. 2E and F and Fig. S7). Notable reductions in originally very high levels of dominance were visible in rice in contribution to calories in Southeast Asia, coconut for fat in Pacific Island countries, and groundnut for fat in central African countries.

As national food supplies became richer for the 52 measured crop commodities and relative abundance patterns of contributing commodities shifted, food supplies worldwide became more similar in composition (inclusive of abundance) for all variables (Fig. 3 and Fig. S8). This increase in similarity brought national food supplies around the planet closer to a global standard composition. Between 1961 and 2009, homogeneity increased by 16.7%, as measured by the mean change in similarity between each country and the global standard composition, with a maximum (single-country) change of 59.7%. Likewise, mean among-country similarity increased by 35.7%. East and Southeast Asian as well as sub-Saharan African countries as regional groups displayed the greatest changes in composition toward the global standard over 1961–2009, in association with the greatest increases in measured crop commodity richness and decreases in dominance.

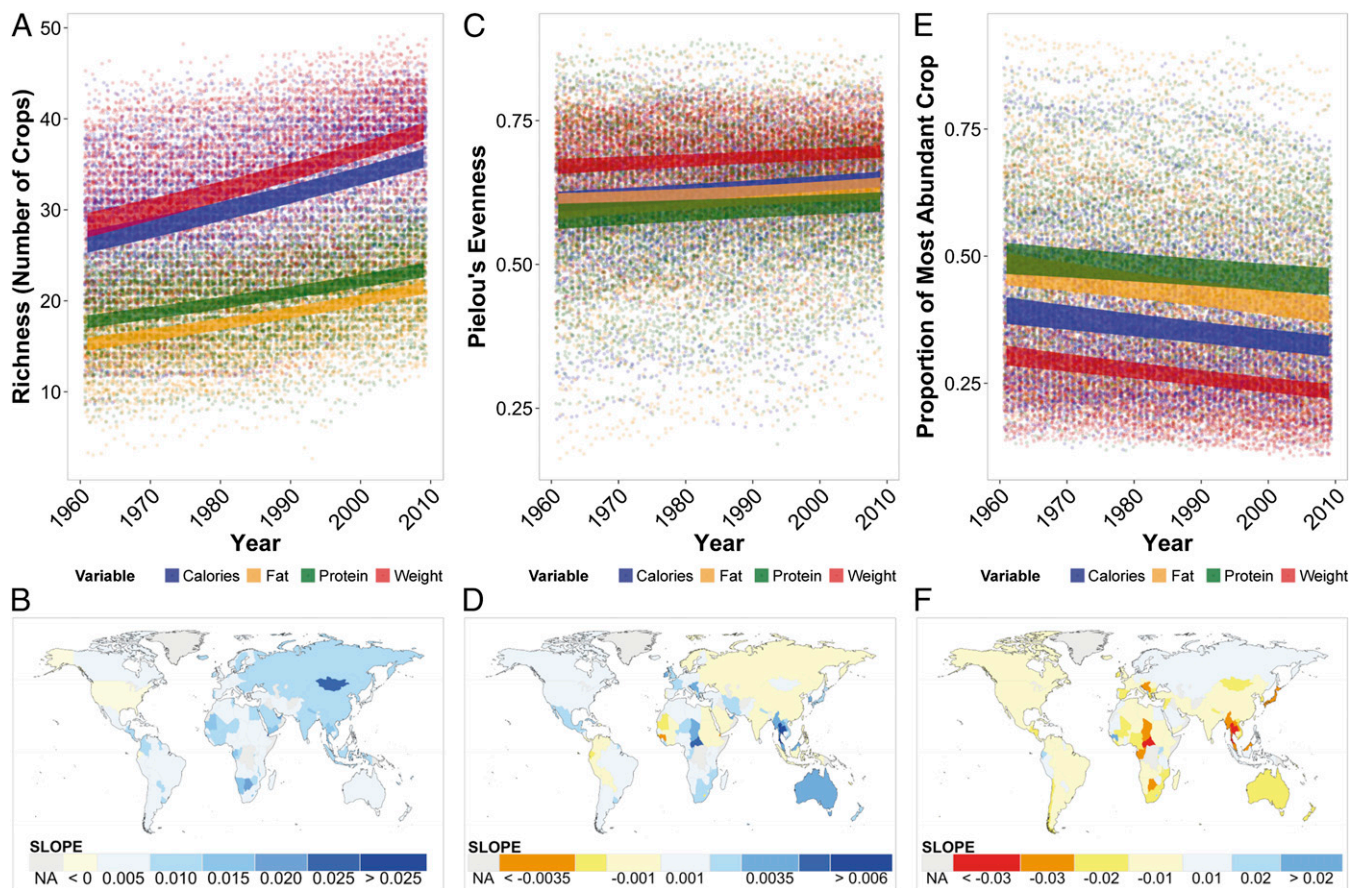
As a measure of the relative importance of crop commodities in total global food supply, inclusive both of plant and animal food sources, we found that 50 of the measured crop commodities currently contribute to the top 90% of calories, protein, fat, and weight around the world. We estimate that these crop commodities are composed of 94 crop species from 70 genera from 37 plant families (Table S1).

### Discussion

The national-level data and multiple variables analyzed here represent the greatest degree of disaggregation of globally comparable food supply data available and thus permit the highest resolution analysis currently feasible for analyzing trends in food crop species utilization worldwide. Food supply data are not directly equivalent to consumption, because food losses at the household level are not measured, but represent a superior measure of the importance of food crops to diets than does production data (27). National-level food supply data both generalizes and underestimates total existing food crop species diversity, because subnational dietary variation, crops primarily encountered in home gardens and local markets, seasonally



**Fig. 1.** Global change in spread and abundance of crop commodities in national food supplies from 1961 to 2009. (A) Slope of the relative change in the geographic spread of crop commodities, defined as the change over time in the presence (i.e., value >0) of a crop commodity in contribution to any variable of food supply in a country in each year. Bars represent slope parameters [ $\pm 95\%$  confidence interval (CI)] from generalized estimation equations with a binomial error distribution, country as a grouping factor, and an autoregressive correlation structure. Sugar; vegetables, other; and fruits, other commodities are not depicted because they were nearly ubiquitous in spread globally throughout the study period and therefore did not change significantly. (B) Slope of the change in relative abundance of crop commodities in contribution to calories, as derived from the value contributed by a particular crop relative to the sum of all crops within a given country within a given year. Bars represent slopes ( $\pm 95\%$  CI) of the predicted values (1961–2009) for each crop from generalized linear mixed models, with year and crop as fixed effects and country as a random effect. Slopes for change in relative abundance of all measurements are depicted in Fig. S3.



**Fig. 2.** Global change in richness, evenness, and dominance of crop commodities in national food supplies from 1961 to 2009. (A) Global mean change in crop commodity richness (i.e., number of crops) in national food supplies. Points represent actual data, and lines are 95% prediction intervals for generalized linear mixed models with a Poisson error distribution. (B) World map displaying the slope of change in crop commodity richness per country for calories. (C) Global mean change in evenness of contributing crop commodities within national food supplies calculated by Pielou's evenness index. Points represent actual data, and lines are 95% prediction intervals for a linear mixed-effects model. (D) World map displaying the slope of change in evenness of national food supplies for calories. (E) Global mean change in the dominance of the most abundant crop commodity in each country in each year. Points represent actual data, and lines are 95% prediction intervals from a generalized linear mixed model with a binomial error distribution. (F) World map displaying the slope of change in dominance in national food supplies for calories.

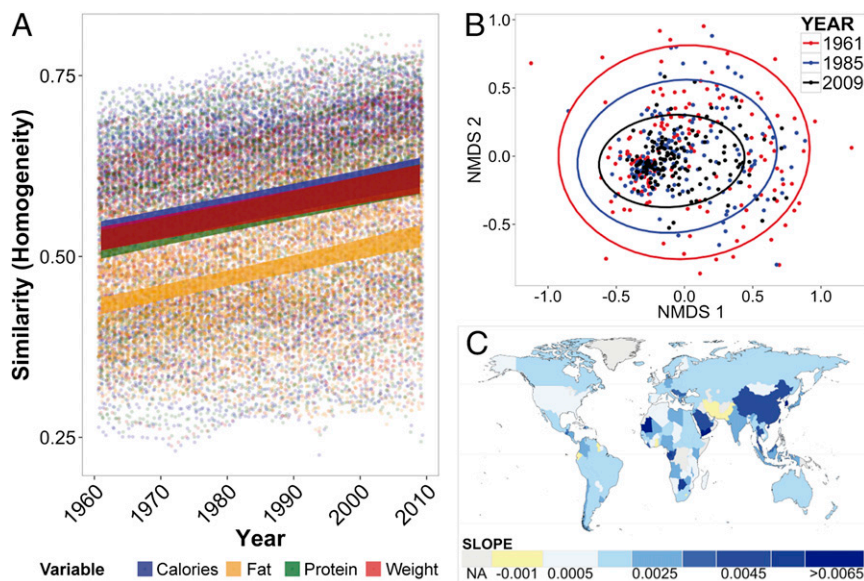
important food plants, and culinary herbs, spices, and other crops consumed in relatively small quantities are not comprehensively reported in national statistics (28). Furthermore, FAO food supply data does not specifically report statistics in regard to micronutrients, where species richness may be particularly significant (21), or assess the indirect contribution to food supply of animal feed and forage plant species. Along with listed crops such as maize and soybean that are major food sources for livestock, global production statistics (29) indicate that crops such as pumpkins, alfalfa, and clover should be recognized as critical indirect contributors to food supply.

More importantly, because of the limited number of individual crop commodities reported by FAO combined with the aggregation of numerous crops into several general commodities, the analyses lack the resolution necessary for elucidating trends in those geographically restricted cereals, legumes, fruits, vegetables, and other crops that may be especially sensitive to changes in the global food system. Although some progress has been made in listing and proposing monitoring strategies for such species (30, 31), substantial improvements in the systems for reporting food production and supply are needed to adequately monitor such crops globally. Ideally, assessments of the state of crop diversity in food supplies would integrate interspecific, varietal, and allelic level analyses of contributing crop plants (26) in

combination with nutritional information (32) and recorded at subnational levels inclusive of regional, community, household, and individual variation (23, 33).

The increased food energy, protein, fat, and weight from plants in food supplies worldwide over the past 50 y appear to primarily have been sourced from globally dominant crops specifically reported by FAO. The total number of important crop species we identified remained relatively consistent in comparison with a previous point estimate based on national-level data from 1979 to 1981 (27), but the spread and abundance values of these crops have changed measurably. The rate of movement toward homogeneity in food supply compositions globally continues with no indication of slowing. This trend implies a likely deterioration in importance of unreported minor and geographically restricted food plants, along with the measured cereal, oil, starchy root, and other crops that displayed significant declines in abundance in national food supplies. Thus, even as the number of measured crops available to the consumer in a given country has increased over the past half-century as a global trend, the total diversity of crops contributing significantly worldwide has narrowed.

A series of interrelated factors are considered to have driven change in food supply compositions worldwide. A primary driver for both diversifying diets and shifting toward increased consumption



**Fig. 3.** Global change in similarity (homogeneity) of food supplies, as measured by Bray–Curtis dissimilarity from each country to the global centroid (mean composition) in each year, converted to similarity. (A) Global mean change in similarity to centroid of national food supplies. Points represent actual data, and lines are 95% prediction intervals from linear mixed-effects models. (B) Multivariate ordination of crop commodity composition in contribution to calories in national food supplies in 1961, 1985, and 2009. Red points represent the multivariate commodity composition of each country in 1961, blue points in 1985, and black points in 2009. Circles represent 95% CIs around the centroid in each year. Between 1961 and 2009, the area contained within these 95% CIs decreased by 68.8%, representing the decline in country-to-country variation of commodity composition (i.e., homogenization) over time. (C) World map displaying the slope of change in similarity to centroid of national food supplies for calories.

of energy-dense foods entails wealth increase and associated gains in purchasing power. Transitions in dietary preferences, particularly toward Western diets (e.g., meat and dairy, wheat, temperate vegetables and fruit, and sugary beverages) have been associated with many facets of globalization and urbanization, including trade liberalization and the development of extensive commodity transport systems, multinational food industries, food quality and safety standardization, mass media, labor changes, smaller family sizes, supermarkets, fast food, processed foods, and human migration. These drivers are detailed elsewhere (22, 23, 33, 34). The modernization and globalization of agriculture through the replacement of human labor with machinery, investments in the breeding and distribution of high-yielding major crops as a development strategy, and subsidies dedicated to a narrow range of crop commodities, among other factors, have further contributed to the increasing global availability of a limited number of major crop plants, with lesser priority given to nutritional diversity (15, 35).

Increases in measured crop-species richness and evenness in food supplies may be considered as indicative of enhanced food security on the local level, particularly in regard to availability and access. However, the increased ability globally to realize within diets the human preference for energy-dense foods (22) based upon a limited number of global crop commodities and processed products has been associated with the rise in non-communicable diseases, such as adult-onset diabetes, heart disease, and certain forms of cancer (22, 23, 34), a trend that is impacting rapidly developing countries such as China more quickly than projected (22). Such dietary changes have also contributed to reductions in diversity in human oral and gut microbiota, which in return have negatively impacted health (36, 37). With the number of overnourished worldwide surpassing the number of undernourished (34), such diseases are becoming epidemics, including within countries still grappling with significant constraints in food availability. Making available and accessible adequate nutritional diversity within and in supplement to the major crops comprising an ever-greater proportion of

global food supplies is critical (14, 18, 32). Engendering consumption patterns cognizant of the impact of food crop choice on health is equally pressing.

The increasing reliance on a suite of truly global crop commodities implies a narrowing in the diversity present in global agricultural systems as a whole, necessitating an equivalent expansion in attention to production stability for these crops (38). The importance of this stability is exacerbated by the necessity of increasing yields of major crops to keep pace with demand, the future success of which has been questioned (39). From a genetic diversity perspective, increasing homogeneity in global food supplies highlights the importance of the breeding and cultivation of varieties of these crops with diverse genetic backgrounds (40, 41). Though varietal diversity, particularly of major cereal crops, can in some regions be relatively high, for other key crops, such as banana, only a handful of varieties are widely cultivated, despite substantial diversity in the gene pool as a whole (42).

Because crop development efforts rely on the utilization of genetic resources (19), it is a policy imperative to ensure the conservation of, and access to, as wide a range of genetic diversity within these global crops as possible, along with the genotypic and phenotypic information necessary to effectively use these resources (43, 44). Unfortunately, significant gaps remain in the conservation of crop genetic resources (45), and access to this diversity requires improvement (46). A number of crops considered here are not sufficiently covered under the pertinent international treaty (47), including plants significant to food supplies globally, such as sugar cane, soybean, and groundnut.

Though our study identifies the major crop commodities critical to national food supplies worldwide, current patterns of production of these crops are not guaranteed given ongoing and predicted changes in climate (48–50), the decline in availability of nonrenewable inputs (51), and increasingly severe impacts of agriculture on soil, water quality, and biodiversity (52). Such trends may impact food security in regard to crop commodity trade (53), decrease the nutritional quality of major crops (54), and enhance the attractiveness of underresearched crop species

(55) that are productive and nutritious given limited inputs, particularly under marginal or variable conditions (56).

Moreover, the importance of crop commodities in food supplies, particularly in contribution to protein and fat, may shift in response to health, natural resources, and climate pressures (22, 57–59), counteracting the trend demonstrated over the past 50 y in increased animal as well as energy-dense plant food commodity consumption. The trajectory of northern European food supplies appears to be demonstrating such a trend (22). Providing that alternative food crops may still be encountered, a further diversification of food supplies with interesting and nutritious crop plants may bolster this evolution.

## Materials and Methods

We analyzed FAO national per capita food supply data for all available measurements [calories (kcal/kilocalories per capita per day), protein (grams per capita per day), fat (grams per capita per day), and weight (grams per capita per day)], from 1961 to 2009, using the full set of commodity and country listings, standardized across all years. Food supply from plants represents national production plus imports plus or minus stock changes over the survey period; minus exports, quantities used for seed, animal feed, and in the manufacture of nonfood products, and losses during storage and transport (27). Plant commodities clearly comprised of the same crop species were aggregated into single commodities representing the crop species, e.g., olive oil and olives. After aggregation, 52 crop commodities remained. Animal foods were included within the crop importance analysis as a single aggregated commodity.

To align all time periods and include as much of the world's population as possible, the current nations formerly comprising the Union of Soviet Socialist Republics, the Socialist Federal Republic of Yugoslavia, the People's Democratic Republic of Ethiopia, and Czechoslovakia were aggregated into their former states, with national data merged by weighted average based on population of the respective states at the respective reporting year. Belgium and Luxembourg were reported together during 1961–1999 and, therefore, recent years listing the countries separately were merged as above. Data for two countries (Occupied Palestinian Territories and Netherlands Antilles) did not appear consistently reported over the study period and were excluded from the analysis. The resulting 152 comparable countries comprised 98% of the world's population across the study period.

Changes in the spread of crop commodities [based on the presence (>0) or absence of a crop in a given country in each year] were analyzed using generalized estimating equations with a binomial error distribution, country as a grouping factor, and an autoregressive (AR-1) correlation structure (i.e., time-lag correlation), using the *geeM* package in R. Slope parameters from these models were extracted to show the direction and magnitude of change for each commodity. Changes in globally aggregated absolute abundance were nonlinear, and were therefore analyzed by subtracting the 1961 abundance value from the 2009 value. Changes in country-level absolute abundance were analyzed the same way, for consistency, and the per-country difference was then averaged across countries. We analyzed changes in relative abundances of crops (i.e., relative to the total value of all crops within a given country) using a generalized linear mixed model with a binomial error distribution, with fixed effects for year and crop, and a random effect of country. Comparisons between crops were performed by estimating the slopes of the predicted values for each crop in the model. Error bars were calculated by estimating the maximum and minimum slope values based on the SEs of the predicted values. Crops for which fat or protein make up less than 1% of their weight were removed from the

analysis for those respective measurements. All mixed-effects models were performed using the *lme4* package in R.

Changes in crop commodity richness in national food supplies were analyzed with generalized linear mixed effects models with a Poisson error distribution and country as a random effect, with random slopes for year, to account for repeated measures over time. The significance of the fixed-effect “year” term in predicting richness was ascertained by conducting a  $\chi^2$  likelihood ratio test on nested models with and without the term. To estimate the differences between countries in change in richness we extracted slope coefficients from the random effects of the mixed-effects model for one measurement type, calories. These coefficients represent the magnitude and direction of the change in richness for each country but do not provide estimates of error. One country (Namibia) displayed a markedly inconsistent jump in richness. The slope for this country was therefore derived from data only from consistent years, with slope parameters estimated by weighted averaging of the slope in consistent time periods. Analyses were performed using the *lme4* package in R.

We used Pielou's evenness index to measure how equally crops contributed to a country's food supplies in a given year, with linear mixed-effects models in the *lme4* package to measure change in evenness over time, as described above. Because Pielou's evenness index can also reflect changes in richness, we additionally analyzed changes in dominance, defined as the change in the proportion of the most abundant crop commodity in each country in each year, using generalized linear mixed models with a binomial error distribution with the *lme4* package in R. For evenness and dominance, slope parameters were extracted from the random effects of the mixed models to estimate the direction and magnitude of the change in each country.

We quantified the homogenization of crop commodity composition using Bray–Curtis distance (dissimilarity) from each country to the global centroid (comparable to the global mean commodity composition, which is inclusive of abundance) in each year using the *betadis* function in the R package *vegan*, with similarity derived by subtracting dissimilarity from 1. A mean increase in similarity to centroid therefore represents a decrease in country-to-country variation, and a homogenization of commodity composition over time. We then used linear mixed models with country as a random factor to assess the significance of the change in similarity to centroid over 1961–2009. Slope parameters were extracted from the random effects of the mixed-effects models to estimate the direction and magnitude of the change in similarity in each country. We also assessed homogenization using a nonmetric multidimensional scaling analysis with Bray–Curtis dissimilarities to compare the mean and variance of commodity composition between three measurement years (1961, 1985, and 2009). Circles for each year represent 95% confidence intervals around the mean; smaller circles indicate lower country-to-country variation in composition.

The number of crop species currently important to food supply was estimated by listing for the most recent year (2009) the plant and animal commodities by decreasing importance until the total contribution equaled 90% of each country's food supply for each measurement, a threshold that is inclusive of major contributors to supply and exclusive of commodities contributing very small quantities (27) (Fig. S9). One biological species per commodity was recognized, except in cases where additional species were clearly likely to contribute to that commodity in at least one listed country. For general commodities, the minimum number of species most likely to contribute was identified (Table S1).

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