LETTER

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National food production stabilized by crop diversity

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Increasing global food demand, low grain reserves and climate change threaten the stability of food systems on national to global scales[1–5]. Policies to increase yields, irrigation and tolerance of crops to drought have been proposed as stability-enhancing solutions[1,6,7]. Here we evaluate a complementary possibility—that greater diversity of crops at the national level may increase the year-to-year stability of the total national harvest of all crops combined. We test this crop diversity–stability hypothesis using 5 decades of data on annual yields of 176 crop species in 91 nations. We find that greater effective diversity of crops at the national level is associated with increased temporal stability of total national harvest. Crop diversity has stabilizing effects that are similar in magnitude to the observed destabilizing effects of variability in precipitation. This greater stability reflects markedly lower frequencies of years with sharp harvest losses. Diversity effects remained robust after statistically controlling for irrigation, fertilization, precipitation, temperature and other variables, and are consistent with the variance-scaling characteristics of individual crops required by theory[8,9] for diversity to lead to stability. Ensuring stable food supplies is a challenge that will probably require multiple solutions. Our results suggest that increasing national effective crop diversity may be an additional way to address this challenge.

During the last decade, drought and extreme heat have caused grain yields to decline in some of the world's major agricultural regions, including Australia (2006–2007)[10], Russia (2010)[11] and the United States (2012)[12]. Resultant increases in global grain prices[4] have worsened access to food, especially for the world's poorest people[11,13,14]. Increasing global crop demand, biofuel mandates and weather-related crop failures can lower grain reserves and increase their annual variability, which increases the sensitivity of food prices to shocks[4,15]. For instance, during the 2008 food crisis—which contributed to political instability in some nations[14,16,17]—global grain stocks fell to just 18% of annual global demand[2]. Because future climatic conditions[18] may cause crop production to become less stable[1], policies and actions are needed to better assure the stability of food supplies on national to global scales.

Different types of policies could increase stability and lessen spikes in food prices; these include using international trade[7,19] and food subsidies[19] to compensate for national crop failures; increasing national yields and reserves; and decreasing national yield fluctuations through the expansion of irrigation or development of drought-resistant crop varieties[1,6,7]. Here, we evaluate a potentially complementary strategy: that growing a more diverse suite of crop species and/or crop groups within each nation might increase the year-to-year stability of national total annual harvest. We term this the crop diversity–stability hypothesis.

Although ecological field experiments have shown that greater plant diversity leads to greater ecosystem productivity and stability[9,20,21], those experiments used non-agricultural perennial plants grown in intermingled mixtures designed to mimic natural ecosystems. By contrast, most crops are annual plants grown in monocultures, calling into question the hypothesis that increased crop diversity might lead to greater year-to-year stability of what we term 'national yield' (defined as the summed annual kilocalorie (kcal) harvest of all edible crops in a nation, divided by the total hectares of cropland). The diversity–stability hypothesis is based on the portfolio effect[8,9], a mathematical theory that predicts the conditions for which the mean (or sum) of random and independent variables would be progressively more stable as more variables are averaged (or summed). When applied to the mix of crops harvested in a nation, this theory gives the conditions for which greater crop diversity would be expected to lead to greater year-to-year temporal stability of the national yield.

We test the crop diversity–stability hypothesis using 50 years (1961–2010) of annual harvest data on 176 crop species for each of 91 populous nations from the FAOSTAT database (Extended Data Table 1). Consultation with the FAO (Food and Agriculture Organization)[22] led to exclusion of five nations with low-quality data (Methods). Temporal stability, S, of national yield is defined as $S = \mu/\sigma$, in which μ is mean national yield (kcal ha^{-1}) for a period of years and σ the year-to-year temporal standard deviation for this period[8]. We calculate S for each of five consecutive ten-year intervals. We use the Shannon information index (H'; see Methods) to quantify crop species diversity and crop group diversity. For crop group diversity, we combined crops into seven crop groups (cereals, vegetables, fruits, pulses, oil crops, sugar crops, stimulants and spices). H' weights each crop species or each crop group in a nation by the proportion of total cropland each occupies. Converting the data from log to linear form—by taking the exponential of H'—gives 'effective' crop species or group diversity, which is the number of equally abundant crop species or groups that are required to obtain the observed H' value. Effective diversity is higher when more crop species, or groups, are grown and when they are more evenly abundant (Extended Data Fig. 1).

We use linear regression to analyse the dependence of national yield stability, mean yield and its temporal standard deviation on effective crop group diversity or, in separate analyses, on effective crop species diversity. We statistically control for mean growing-season precipitation and temperature, or for the year-to-year temporal instability of growing season precipitation and temperature (derived from Climate Research Unit data), as well as for rates of fertilization and irrigation (from FAOSTAT) and warfare (Center for Systematic Peace, Extended Data Table 1).

In all analyses, including many variants (Methods), temporal stability of national yield strongly increases with effective crop group and species diversity, and with irrigation (Fig. 1a, b, Extended Data Fig. 2 and Extended Data Table 2 a, b). Small increases in stability lead to greatly decreased probabilities of years with major declines in national yield (Fig. 2). On average, a nation with a mean stability of 5 experiences a national yield decline of more than 25% once every 8 years (probability of 0.16; Fig. 2), whereas nations with stabilities of 7.5, 10 or 15 have yield declines of more than 25% only once every 21, 54 or 123 years, respectively (probabilities of 0.048, 0.0215 and 0.0081, respectively; Fig. 2).

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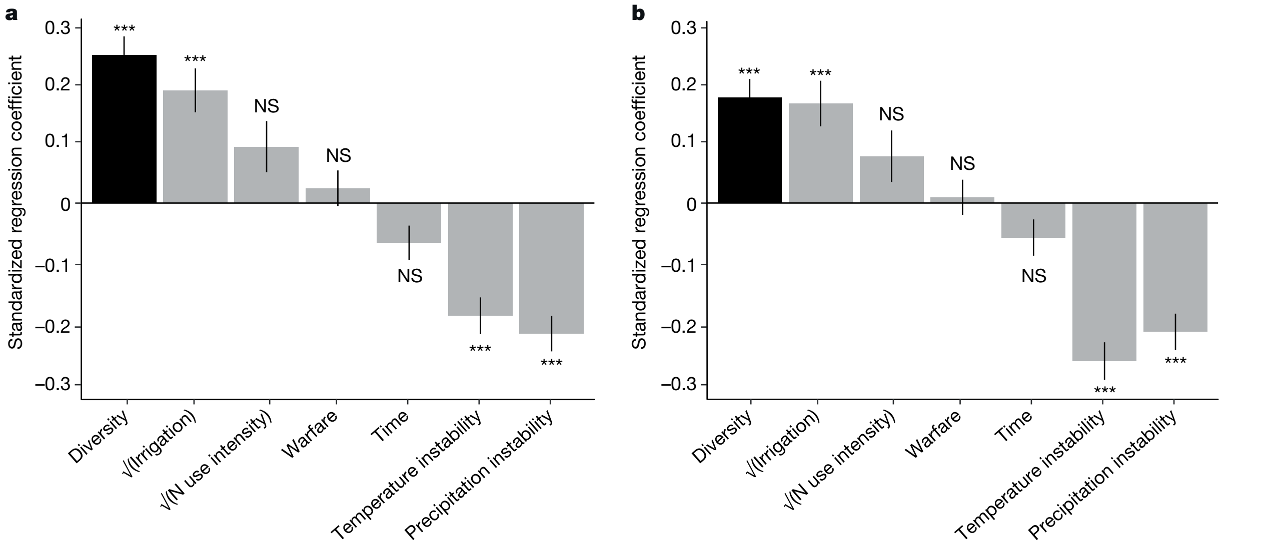

Fig. 1 | Determinants of national caloric yield stability. Regression coefficients (±s.e.) show the magnitude of the effect of each variable in a multiple regression of $\log_e$(national yield stability). **a**, Regression coefficients using effective crop group diversity ($n = 437$). **b**, Regression coefficients using effective crop species diversity ($n = 437$). Each predictor variable was standardized to zero mean and unique variance across all nations and time periods (Methods) to enable the comparison of effects with a change of 1σ in each predictor on the log(stability) values. Asterisks indicate the significance of each predictor. $^{***}P < 0.001$; NS, not significant ($P > 0.05$).

Both effective crop diversity and irrigation have significant stabilizing effects that are opposite in direction and about equal in magnitude to those of observed precipitation instability and temperature instability (Fig. 1a, b and Extended Data Fig. 2). The effects of crop diversity on national yield stability remained positive and significant when our analyses included only effective species or group diversity (Extended Data Table 3a, b), and when they also included seven other variables in addition to those included in Fig. 1 (Extended Data Table 3c, d). The area of each nation, organic carbon content of the soil and trade were weakly significantly related to national yield stability. Additional analyses support the robustness of these results (Extended Data Tables 4–7), including mixed-effect models with nations as a random effect and with additional controls for data quality (Extended Data Table 4).

Both effective crop group and species diversity stabilized national yield by decreasing σ, its year-to-year variation (Fig. 3a, c). This greater stability is consistent with the portfolio effect[9], which requires that $z > 1$, in which z is the empirically observed scaling coefficient for the dependence of year-to-year variances (σ_i^2) in national yields of each individual crop (i) on m_i, the decadal mean yield of each crop[9] (with data for all crops, i, fit to $\sigma_i^2 = c\mu_i^z$; Methods). For crop species, $1.98 < z < 2.23$ and for crop groups $1.58 < z < 1.97$, which are consistent with the portfolio effect's criterion of $z > 1$ for diversity to lead to stability.

Yield stability is also greater as mean precipitation increases (Extended Data Table 5a, b). Conversely, the stability of national yield is lower in nations with higher year-to-year temporal instability of growing-season precipitation and temperature (Fig. 1a, b), supporting a recent study[3]. Because stability is $S = \mu/\sigma$, higher stability may arise from a lower temporal standard deviation and/or a higher mean yield. Notably, mean national yield is statistically independent of effective crop species diversity (Fig. 3d and Extended Data Table 2a, b). However, national yield is positively dependent on crop group diversity (Fig. 3c and Extended Data Table 2a), perhaps because crop rotations (for example, cereals and legumes[23]) increase yields. This yield effect may explain why crop group diversity has a greater stabilizing effect than crop species diversity (Fig. 1). The stabilizing effects of irrigation reflect both higher mean yields (Fig. 3c, d) and lower temporal standard deviations (Fig. 3a, b). By contrast, nitrogen fertilization increases the temporal standard deviation by approximately the same amount as it increases mean yield (Fig. 3) and therefore does not significantly stabilize yield (Fig. 1a, b and Extended Data Table 2a, b). Nonetheless, higher yields from irrigation and fertilization could be used to increase crop reserves and to therefore buffer national food supplies.

Our analyses provide robust, albeit correlational, support for the hypothesis[24] that greater effective national crop diversity leads to greater year-to-year stability of national yield. Most empirical evidence of the stabilizing effects of crop diversity on total yield has come from field-scale[23,25,26] and landscape-scale studies[27]. When we aggregated national data into each of seven FAO-derived geographical regions (Methods), we found that regions with greater effective crop diversity had greater stability of their regional food supply (Extended Data Table 6a, b). Finally, in analyses using the total national annual

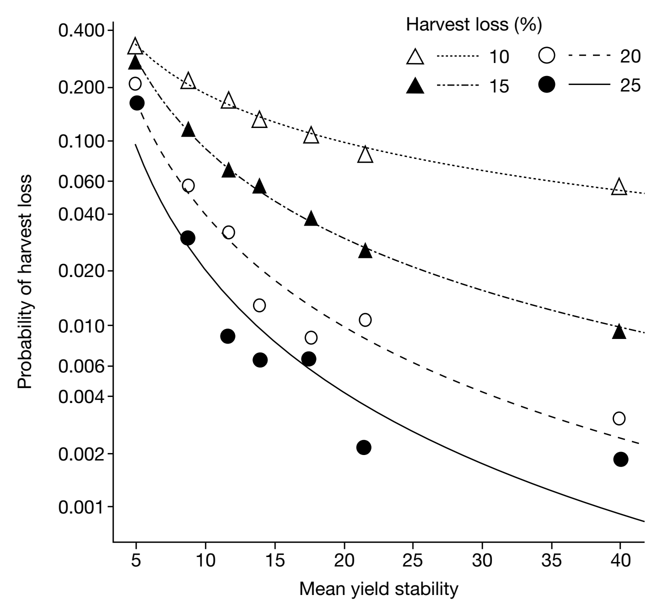

Fig. 2 | National yield stability and probabilities of crop harvest losses. Observed probabilities (logarithmic scale) of national annual yield being more than 10, 15, 20 or 25% less than the decadal mean of that nation. Decadal probabilities were calculated after assigning decadal results for each nation ($n = 437$) to one of seven decadal stability bins (Methods). Curves show the observed probability of a given level of harvest loss, fitted using a log–log model, against the mean stability of each bin.

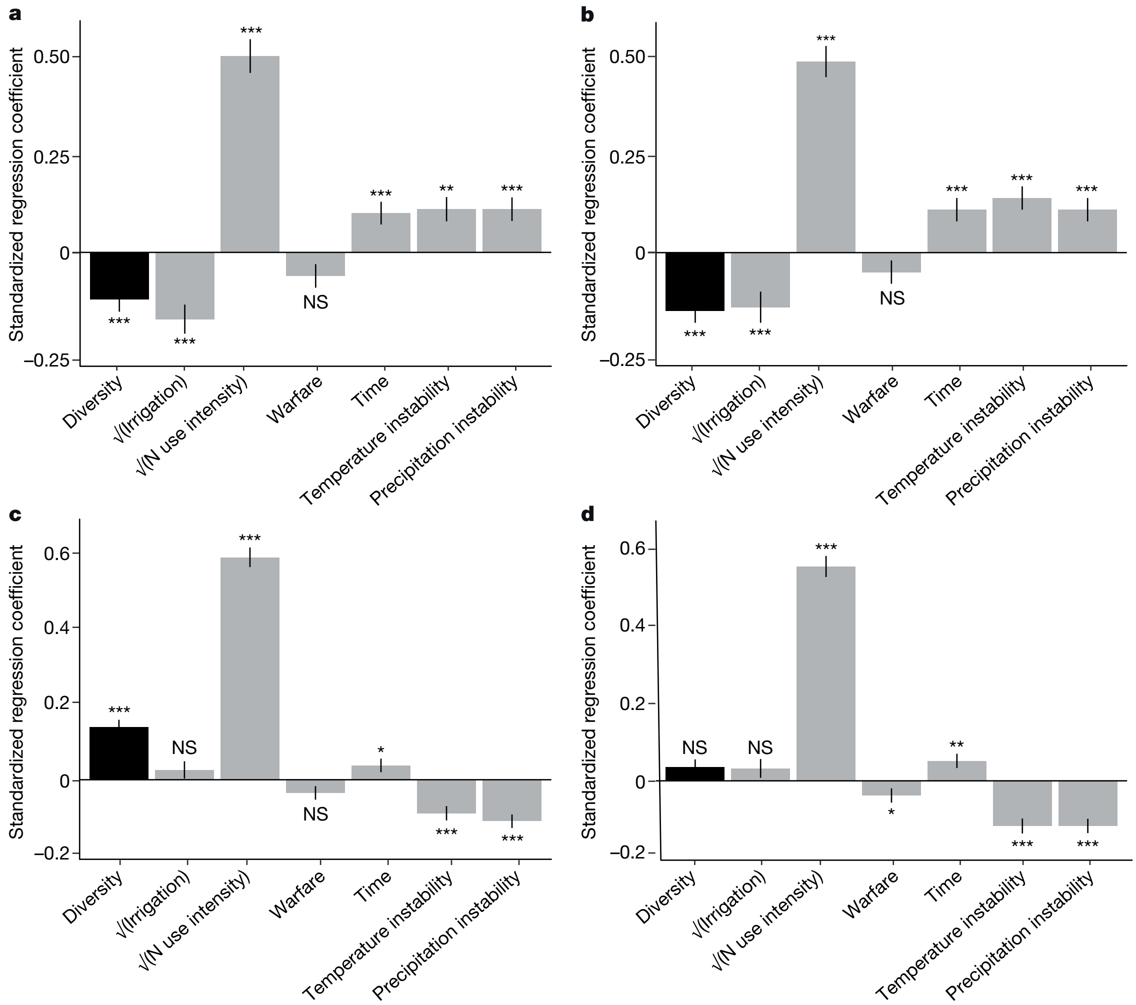

Fig. 3 | Determinants of temporal variation and mean national caloric yield. a–d, Regression coefficients (±s.e.) for all variables in multiple regressions of $\log_e$-transformed temporal standard deviation of national yield (**a**, **b**) and $\log_e$-transformed mean national yield (**c**, **d**), for regressions using effective crop group diversity (**a**, **c**; $n = 437$) or effective crop species diversity (**b**, **d**; $n = 437$). Each predictor variable was standardized to zero mean and unique variance across all nations and time periods. $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

economic value of all crops (Methods), we found that national agricultural economic yield is also significantly more stable in nations with higher effective crop diversity (Extended Data Table 7a, b). Future studies should also explore how crop choice and diversity may be related to nutrition, affordability and sufficiency.

If, as forecasted, climate change increases the frequency of water-limited yields[18], nations that increase effective crop diversity might decrease the yield instability that could otherwise occur. Such efforts could complement the benefits of new drought-tolerant crop varieties[28], increased irrigation, intercropping[29] and greater and more transparent trade[7]. Greater crop diversity may be particularly useful in nations with water-limited yields[30] where irrigation is unaffordable or water is insufficient for increased irrigation, and where farmers might stabilize family income and food supply through higher crop diversity. Our analysis at the national scale did not reveal that particular crop groups contributed more to yield stability (Methods and Extended Data Fig. 3). Rather, attaining the benefits of higher crop diversity may require identifying those combinations of crops or crop groups that optimize yield stability in each nation.

Ensuring stable food supplies during an era of rapid population growth and climate change is a challenge that will require multiple solutions. Our results suggest that increasing national effective crop diversity merits deeper exploration and consideration as an additional, but currently overlooked, way to stabilize national food supplies and reduce the risk of crop failures.

Online content

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1. Rosenzweig, C. & Parry, M. L. Potential impact of climate change on world food supply. *Nature* **367**, 133–138 (1994).
2. Fraser, E. D. G., Legwegoh, A. & Krishna, K. C. Food stocks and grain reserves: evaluating whether storing food creates resilient food systems. *J. Environ. Stud. Sci*. **5**, 445–458 (2015).
3. Ray, D. K., Gerber, J. S., MacDonald, G. K. & West, P. C. Climate variation explains a third of global crop yield variability. *Nat. Commun*. **6**, 5989 (2015).
4. Marchand, P. et al. Reserves and trade jointly determine exposure to food supply shocks. *Environ. Res. Lett*. **11**, 095009 (2016).
5. Challinor, A. J. et al. Transmission of climate risks across sectors and borders. *Phil. Trans. R. Soc. A* **376**, 20170301 (2018).
6. Lobell, D. B. et al. Prioritizing climate change adaptation needs for food security in 2030. *Science* **319**, 607–610 (2008).
7. Bailey, R. et al. *Extreme Weather and Resilience of the Global Food System. Final Project Report from the UK–US Taskforce on Extreme Weather and Global Food System Resilience* https://www.foodsecurity.ac.uk/publications/archive/page/4/ (The Global Food Security Programme, 2015).
8. Doak, D. F. et al. The statistical inevitability of stability–diversity relationships in community ecology. *Am. Nat*. **151**, 264–276 (1998).

9. Tilman, D. The ecological consequences of changes in biodiversity: a search for general principles. *Ecology* **80**, 1455–1474 (1999).
10. Huai, J. Dynamics of resilience of wheat to drought in Australia from 1991–2010. *Sci. Rep.* **7**, 9532 (2017).
11. Bren d'Amour, C., Wenz, L., Kalkuhl, M., Steckel, J. C. & Creutzig, F. Teleconnected food supply shocks. *Environ. Res. Lett.* **11**, 035007 (2016).
12. Rippey, B. R. The US drought of 2012. *Weather Clim. Extrem.* **10**, 57–64 (2015).
13. Harvey, C. A. et al. Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. *Phil. Trans. R. Soc. B* **369**, 20130089 (2014).
14. Sternberg, T. Chinese drought, bread and the Arab Spring. *Appl. Geogr.* **34**, 519–524 (2012).
15. Rosset, P. Food sovereignty and the contemporary food crisis. *Development* **51**, 460–463 (2008).
16. Fader, M., Gerten, D., Krause, M., Lucht, W. & Cramer, W. Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. *Environ. Res. Lett.* **8**, 014046 (2013).
17. Puma, M. J., Bose, S., Chon, S. Y. & Cook, B. I. Assessing the evolving fragility of the global food system. *Environ. Manage.* **10**, 024007 (2015).
18. IPCC. *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. et al.) (Cambridge Univ. Press, 2007).
19. FAO. *Soaring Food Prices: Guide for Policy and Programmatic Actions at Country Level to address High Food Prices*. http://www.fao.org/fileadmin/user_upload/ISFP/revisedISFP_guide_web.pdf (2011).
20. Cardinale, B. J. et al. Impacts of plant diversity on biomass production increase through time because of species complementarity. *Proc. Natl Acad. Sci. USA* **104**, 18123–18128 (2007).
21. Gross, K. et al. Species richness and the temporal stability of biomass production: a new analysis of recent biodiversity experiments. *Am. Nat.* **183**, 1–12 (2014).
22. Tubiello, F. N. Make better use of UN food and agriculture stats. *Nature* **563**, 35 (2018).
23. Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M. & Liebman, M. Increasing cropping system diversity balances productivity, profitability and environmental health. *PLoS ONE* **7**, e47149 (2012).
24. Lin, B. B. Resilience in agriculture through crop diversification: adaptive management for environmental change. *Bioscience* **61**, 183–193 (2011).
25. Snapp, S. S., Blackie, M. J., Gilbert, R. A., Bezner-Kerr, R. & Kanyama-Phiri, G. Y. Biodiversity can support a greener revolution in Africa. *Proc. Natl Acad. Sci. USA* **107**, 20840–20845 (2010).
26. Gaudin, A. C. M. et al. Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS ONE* **10**, e0113261 (2015).
27. Abson, D. J., Fraser, E. D. & Benton, T. G. Landscape diversity and the resilience of agricultural returns: a portfolio analysis of land-use patterns and economic returns from lowland agriculture. *Agric. Food Secur.* **2**, 2 (2013).
28. Challinor, A. J., Koehler, A.-K., Ramirez-Villegas, J., Whitfield, S. & Das, B. Current warming will reduce yields unless maize breeding and seed systems adapt immediately. *Nat. Clim. Change* **6**, 954–958 (2016).
29. Raseduzzaman, M. & Jensen, E. S. Does intercropping enhance yield stability in arable crop production? A meta-analysis. *Eur. J. Agron.* **91**, 25–33 (2017).
30. Lesk, C., Rowhani, P. & Ramankutty, N. Influence of extreme weather disasters on global crop production. *Nature* **529**, 84–87 (2016).

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METHODS

Agricultural dataset. We obtained national annual crop area harvested (in hectares), crop production (in tonnes) and gross market value (in constant 2004–2006 international dollars) from 1961 to 2010 for each of 176 crops in each of 100 populous nations (representing 89% of the global 2010 population and 91% of the global crop production) from the FAOSTAT database (URLs to each database are included in Extended Data Table 1). On the recommendation of staff at the FAO, we accounted for differences among nations in data quality, which led us to remove five nations for which at least 20% of the data on area harvested or production had to be estimated by the FAO. To identify those nations with high rates of estimated data (rather than data communicated directly by nations), we calculated the weighted proportion of species-specific data corresponding to each type of flag used by the FAO to indicate how the data were obtained, with the weight being the proportion of total production that each crop species represents for a nation in a given decade. When the proportion of estimated data per decade and nation was added as a variable in our analyses of stability, it was significant with the entire dataset, and not significant in all but a few analyses once the five nations were removed. The excluded nations were North Korea, Guinea, Kenya, Mozambique and Zambia. Because some countries had one or more decadal time periods in which more than 20% of weighted yield data were estimated, we did an additional set of analyses in which all 68 of such decadal results were excluded from analyses. Because Ireland, New Zealand and Netherlands use much of their fertilizer on pastures rather than for croplands, and because we could not find data on the amounts used in this manner, they were excluded from the models. Egypt, which has 100% of cropland equipped with irrigation for the 5 decades, was also removed from the models. For all other nations, for each year, we calculated the total annual caloric yield (millions of kcal ha^{-1}) of each nation by (1) multiplying the production of each of its crops by commodity-specific kcal conversion factors from the USDA Nutrient Database[31] to get the kcal production of each crop; (2) summing these kcal harvests across all crops; and (3) dividing this sum by the sum of all harvested land for all crops. In doing this, we used the full set of 176 plant crop species reported by FAO. We calculated the total annual economic yield (in constant 2004–2006 1,000 international dollars per ha) of each nation for each year by multiplying amounts harvested by their market prices, then summing these values and finally by dividing this sum by the sum of all of its harvested land for all these crops.

National crop yield stability and effective crop species and group diversity. We quantified national crop yield stability (for caloric and economic yield), S, as the ratio of mean national yield (μ) over its temporal standard deviation (σ); $S = \mu/\sigma$. S, in essence, is the inverse of the coefficient of variation. To do this, we divided the 50-year time period covered by the data into 5 non-overlapping intervals of 10 years each. We next removed national yield variation attributable to a temporal trend of increasing crop yield by regressing annual crop yields on year squared for each decade and nation. For each of such decadal regression, the σ of the residuals provided the measure of detrended variation of national yield that was used to calculate the temporal stability of national yield. We then used the μ for each ten-year interval for each nation, and its associated detrended σ to calculate yield stability for each nation and decade. To identify crop groups that contributed the most to stabilizing national yield, we calculated national yield stability when dropping each crop group, one at a time, over the entire time period. Let S'_i be the value of national yield stability when crop group i is deleted, and let S be the national yield stability with all crop groups are included. The log(response ratio), $-\ln(S'_i/S)$, is positive if removing crop group i has a stabilizing effect and is negative if removing crop group i has a destabilizing effect (Extended Data Fig. 3).

For each nation and year, we used the proportion of the total harvested area occupied by each crop species (or each crop group: cereals, vegetables, fruits, pulses, oil crops, sugar crops, stimulants and spices, as defined by the FAO) to calculate the Shannon diversity index (H') and thus the effective diversity[32] of crop species or crop groups as $\exp(H')$. If p_i is the proportion of total national cropland dedicated to crop i (or to crop group i), and N is the total number of crop species (or crop groups), $H' = -\sum_{i=1}^{N}(p_i \ln[p_i])$. To align measures of stability with diversity, we calculated mean effective crop species diversity and mean effective crop group diversity for each nation for each of the five decadal time periods.

Agricultural management, social, economic, political and weather data. For each nation studied, we compiled annual national-level data on the rate of agricultural inputs (mineral fertilizers and irrigation), warfare and weather. Because of major disparities in the availability of data on the use of modern seed varieties among nations and time periods, data on seed varieties were not included in our analyses. We used data from the FAOSTAT database on the annual total national application of nitrogen, and the total cropland area irrigated. We calculated the rate of application per hectare of each of these inputs by dividing their use by the total area harvested for all crops. The Center for Systematic Peace provided data on the summed magnitude of all the major episodes of political violence (MEPV, referred to as 'warfare' in the main text) that include seven categories of armed conflicts that resulted in deaths[33]. We obtained global gridded climatic data from the Climate Research Unit of the University of Anglia (CRU TS v.3.23)[34]. From these data, we derived monthly precipitation (mm) and temperatures (degrees Celsius) for the cropland area in each nation by taking the monthly precipitation and temperature values of each grid cell in a nation, weighted by the proportion of cropland in each grid cell[35]. Then, we calculated national precipitation and temperature across annual growing seasons by averaging monthly weather values over months of nation-specific crop-growing-season calendars[36]. We calculated the mean magnitude of all MEPV, rate of fertilizer use and irrigation over each of the five ten-year time periods. For weather, we calculated the μ, σ and instability ($-(\mu/\sigma)$) of cropland-based growing-season-specific temperature and precipitation for each nation and for each of our five ten-year time periods.

Observed probabilities of national harvests below decadal means. To quantify how national yield stability is related to the probability of a national yield loss, we calculated the probability, for each decade, that the observed yield of a nation in a given year is at least a specified percentage less than the mean yield for that nation in that decade. To do this, we first sorted and grouped all nations and all decades into seven bins according to their decadal stability values. The first six bins (1–6) each contain 470 national decadal observations, with these bins having stability means of 4.84, 8.71, 11.64, 13.88, 17.64 and 21.58, respectively. The seventh bin, with a mean stability of 40.05, is deliberately larger to better reveal the tail of this stability value distribution, and contains 1,880 observations. We then standardized the annual yield of each nation per decade so that the mean yield of all observations in each bin was equal to one. Finally, for each bin, we determined the number of observations with a standardized annual yield below 0.90, 0.85, 0.80 or 0.75. Each of these numbers was divided by the total number of observations in that bin to obtain the observed probability of yield loss of more than 10% (for the yield less than 0.9), 15%, 20% or 25%, respectively (Fig. 2).

Data aggregation at the scale of geographical regions. We aggregated caloric and economic yield, crop diversity and data on agricultural management, social and weather across the six geographical regions defined by the FAO. To do this, for each year, we summed the area harvested, food production and crop market value (in constant 2004–2006 1,000 international dollars) across all crop species and across nations in each geographical region. Area equipped for irrigation and the use of nitrogen were summed across nations in each region and divided by the summed area harvested. We derived monthly regional precipitation (mm) and temperatures (degrees Celsius) by (1) multiplying the monthly precipitation and temperature values of each grid cell in each nation in each region and (2) obtained a weighted average at the regional scale by summing the values obtained in (1) and divided this value by the total proportion of cropland across all the cells in a region. Because warfare (MEPV) is a magnitude score, it does not sum up across nations. Instead, we calculated an annual average of the MEPV score across nations in each geographical region and then a temporal average of these annual values across ten years.

Statistical analyses. We used linear regression models to test whether national crop yield stability (either caloric or economic yield) depended on effective crop species diversity or effective crop group diversity, respectively, across nations and time periods. To normalize residuals, we log-transformed national yield stability, μ and σ. In addition to either effective crop species diversity or effective crop group diversity, each regression model included time (five decadal time periods as a continuous variable), rate of nitrogen application and percentage of cropland irrigated (both square-root-transformed), warfare, temperature and precipitation instability. Each of the predictor variables in our model had a variance inflation factor value lower than two, which indicates that collinearity among variables was not an issue. We ran a separate set of regressions that was identical to these but used mean temperature and precipitation instead of their instability. Because predictors used in our models were measured in different units and have various ranges of values, we standardized each predictor, across all nations and over the full 50-year time period, to have zero mean but its own unique variance. This transformation, performed before analyses, enabled quantitative comparisons of the resulting model coefficients for the variables. To determine whether stability effects resulted from an increase in mean yield, a decrease in detrended temporal yield σ or both, we performed additional regressions (Extended Data Tables 2, 4–7).

To test the robustness of our results, we performed several additional analyses. First, we included country as a random effect in the analyses discussed above and obtained similar effective crop diversity effects (Extended Data Table 4b). Second, we used the simplest possible model, with the only predictor being effective crop species or group diversity (Extended Data Table 3a, b). We also simplified our model by accounting only for the predictors of yield stability that were significant in the complete model (that is, effective crop species and group diversity, weather instability, irrigation and time). Fourth, we considered additional predictors that might influence national yield stability (Extended Data Table 3). Specifically, we added to the model of Fig. 1: geographical regions, elevation range calculated from the USGS global data[37], the diversity of soil types in cropland within each nation calculated from the FAO/UNESCO digital soil map of the world[38], the soil organic content, language diversity index[39] as a measure of cultural diversity, the country area from FAOSTAT database[39] and the engagement of each nation in trade[40]. In all cases, we found that both adding all these variables, and deleting most or all but effective diversity, did not change the highly significant dependence of stability on effective crop group and species diversity (Extended Data Table 3c, d). We next tested the crop diversity–stability relationship across geographical regions, including regions in the model (Extended Data Table 6). All of the statistical analyses were performed using JMP Pro[41] and geostatistical treatment with QGIS[42]. Additionally, we used the highly conservative dataset from which the 68 decadal periods with estimated values greater than 20% were also excluded. Analyses found that stability was similarly significantly dependent on effective crop species diversity, irrigation, precipitation instability and temperature instability in a regression, and that the weighted proportion of estimated values was not significant (Extended Data Table 4a). We found similar results when regression models included nation as a random effect (Extended Data Table 4b). Finally, we repeated the above analyses using the full original dataset from which no data had been excluded, and consistently found significant positive effects of effective crop diversity on stability.

Test of the portfolio effect. To test whether greater national yield stability at higher effective crop species or group diversity is consistent with the portfolio effect, we quantified how the inter-annual variance (σ_i^2) in the yield of each individual crop species, *i*, depended on its mean yield (μ_i), as $\sigma_i^2 = c\mu_i^z$ thus calculating the scaling coefficient[9] z. Such scaling leads to the prediction that the temporal stability, S_N, of a system with an effective crop species diversity of N would be $S_N = S_1 N^{(z-1)/2}$, in which S_1 is the average stability of a single crop species[43]. Theory states that diversity leads to stability when $z > 1$.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this paper.

Data availability

The sources of all data used in this study are referenced in the Methods and all raw data are freely accessible at the URLs provided in Extended Data Table 1. The dataset used for the analyses is available from the corresponding author upon request.

31. United States Department of Agriculture. *National Nutrient Database*. https://ndb.nal.usda.gov/ (2013).
32. Hill, M. O. Diversity and evenness: a unifying notation and its consequences. *Ecology* **54**, 427–432 (1973).
33. Marshall, M. G. *Codebook: Major Episodes of Political Violence (MEPV) and Conflict Regions, 1946–2015*. http://www.systemicpeace.org/inscr/MEPVcodebook2015.pdf (2016).
34. Harris, I., Jones, P. D., Osborn, T. J. & Lister, D. H. Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 dataset. *Int. J. Climatol.* **34**, 623–642 (2014).
35. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Glob. Biogeochem. Cycles* **22**, GB1022 (2008).
36. Sacks, W. J., Deryng, D., Foley, J. A. & Ramankutty, N. Crop planting dates: an analysis of global patterns. *Glob. Ecol. Biogeogr.* **19**, 607–620 (2010).
37. Danielson, J. J. & Gesch, D. B. *Global Multi-Resolution Terrain Elevation Data 2010 (GMTED2010)*. https://pubs.usgs.gov/of/2011/1073/pdf/of2011-1073.pdf (US Geological Survey, 2011).
38. FAO-UNESCO. *Soil Map of the World: Revised Legend (with Corrections and Updates). World Soil Resources Report 60* http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/ (FAO, 1988).
39. Simons, G. F. & Fennig, C. D. *Ethnologues: Languages of the World* 21st edn (SIL International, 2017).
40. MacDonald, G. K. et al. Rethinking agricultural trade relationships in an era of globalization. *Bioscience* **65**, 275–289 (2015).
41. JMP v.12.0.1 (SAS Institute, 2007).
42. Quantum GIS Development Team. *Quantum GIS Geographic Information. version 2.13* (2016).
43. Tilman, D. Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. *Proc. Natl Acad. Sci. USA* **96**, 5995–6000 (1999).

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Additional information

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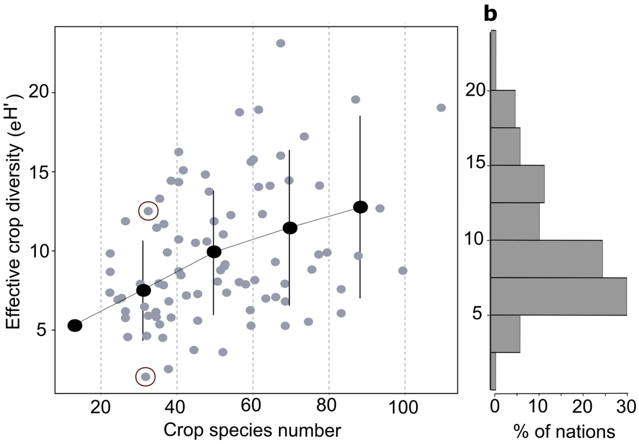
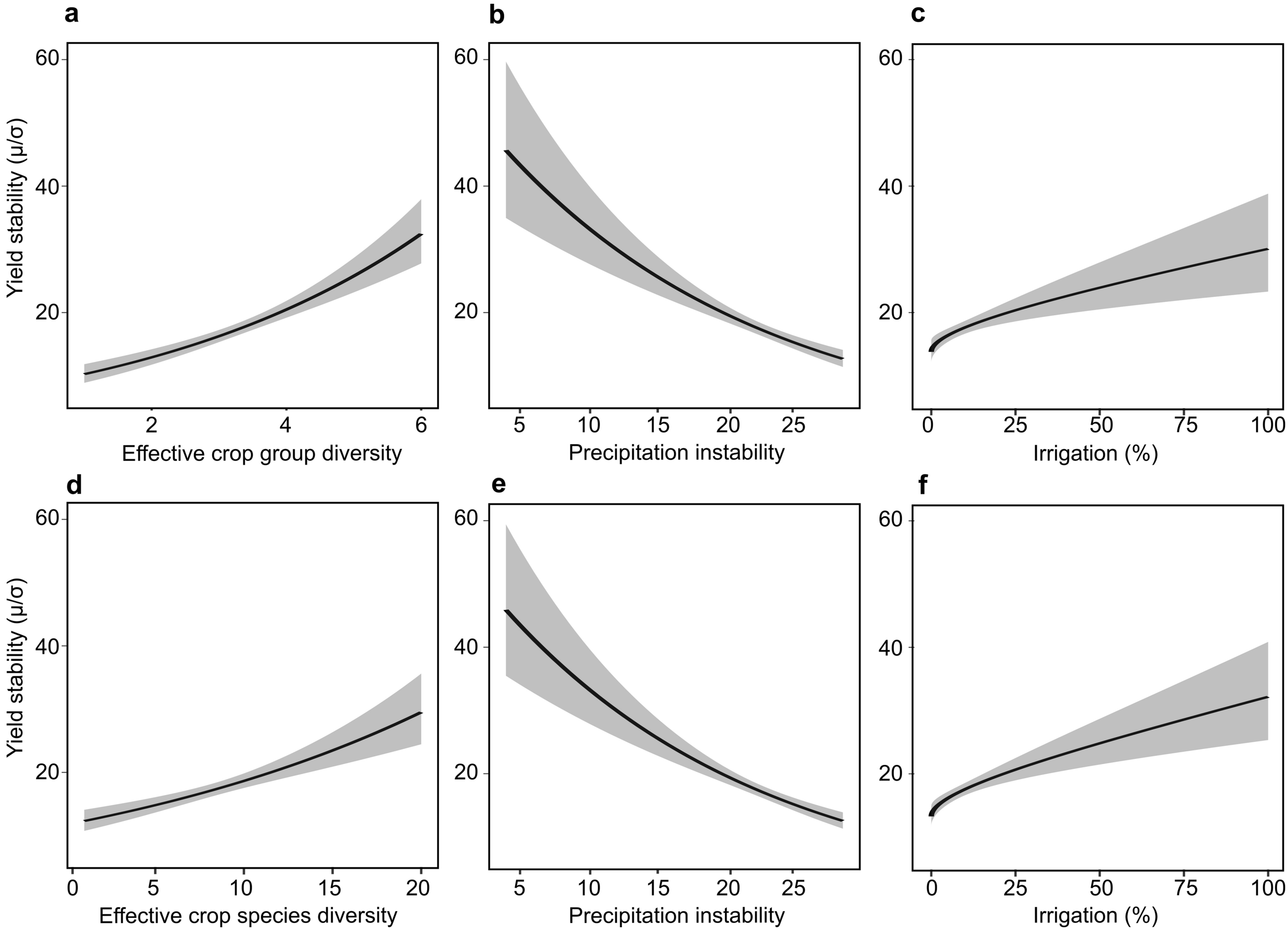
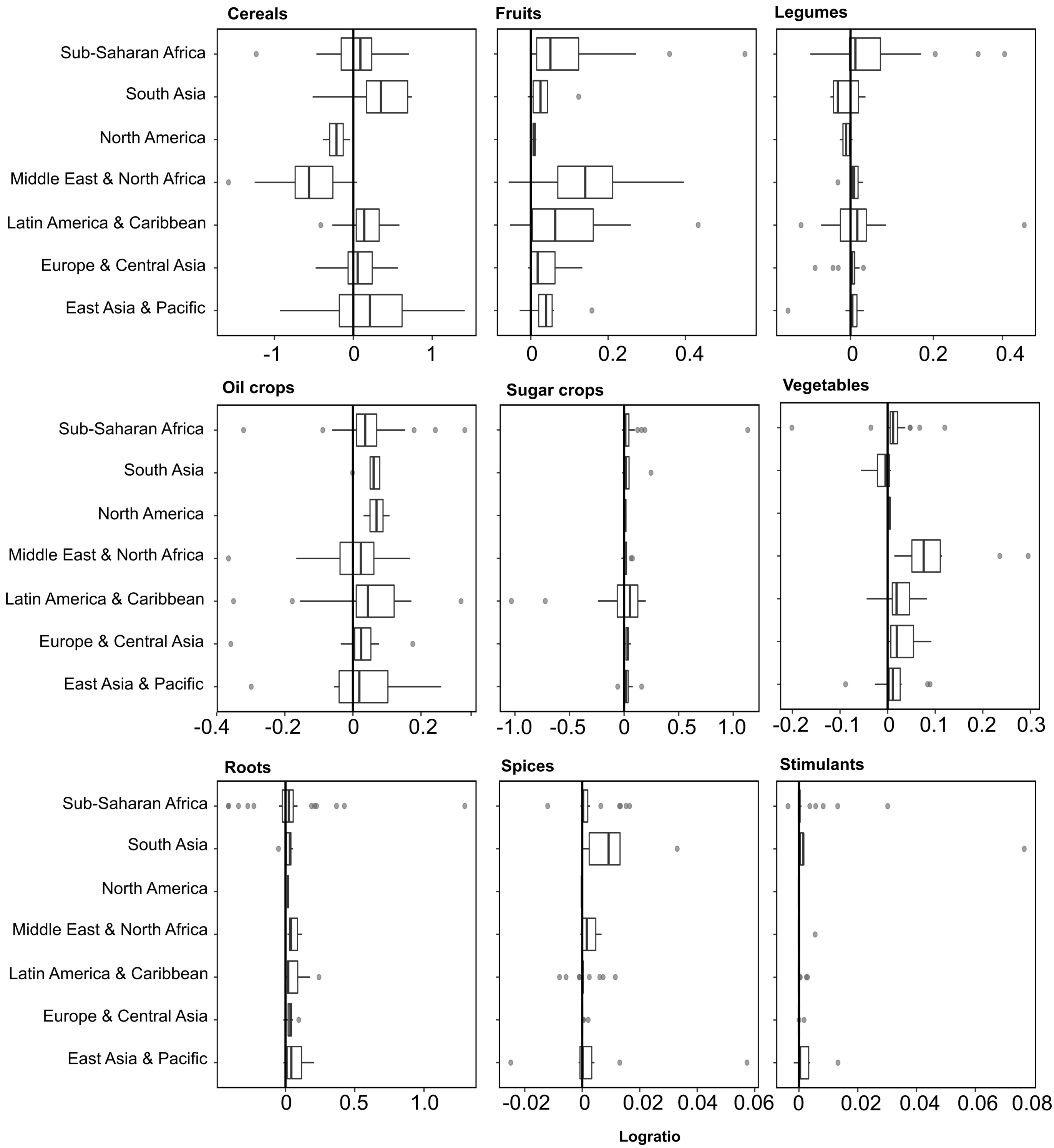


Extended Data Fig. 1 | Relationship between effective crop species diversity and crop species number per nation. a, Black dots are mean effective crop species diversities and bars show the σ for nations grouped as planting 1–20, 20–40, 40–60, 60–80 or 80–100 crop species during 2001–2010 ($n = 91$). Data for each nation are shown as grey dots. Note that for a given number of crop species, there is a wide range in their effective crop species diversity caused by some nations having only a few dominant crops (and thus having a low effective diversity) and other nations having many crops of more similar abundances (and thus a high effective diversity). The two circled dots highlight 2 such nations, both growing 30 crop species but either very unevenly (that is, the dot with low effective diversity) or more evenly (that is, the dot high effective diversity). **b**, The frequency distribution of the effective crop species diversity values for this same time period.



Extended Data Fig. 2 | Main determinants of national caloric yield stability. a–f, Magnitude of the change in national yield stability as dependent on effective crop group diversity (**a**) and effective species diversity (**d**), precipitation instability (**b**, **e**) and irrigation (**c**, **f**). **a–c**, Values of national yield stability are predictions from the multiple regression model using effective crop group diversity (Extended Data Table 2a). **d–f**, Values of national yield stability are predictions from the multiple regression model using effective crop species diversity (Extended Data Table 2b). Predicted values were back-transformed from log-transformation, calculated using the observed range of the three predictors and keeping all the other predictors at their mean values. The grey bands represent the regression 95% confidence interval.



Extended Data Fig. 3 | Contribution of crop groups to national caloric yield stability for each of six geographical regions. A positive value of the log-transformed response ratio of yield stability for a crop group indicates that the presence of that crop group has a stabilizing effect. A negative value indicates a destabilizing effect. National log response ratios are represented per geographical region. In most regions, the presence of a given crop group is associated with increased national yield stability ($n = 819$).

Extended Data Table 1 | Sources of data supporting findings

Data	References	Name of the data set	URL
Agricultural data set			
Area harvested	[31]	Crops	http://www.fao.org/faostat/en/#data/QC
Crop production	[31]	Crops	http://www.fao.org/faostat/en/#data/QC
Crop market value	[31]	Value of agricultural production	http://www.fao.org/faostat/en/#data/QV
Kcal conversion factors	[32]	USDA Food Composition Databases	https://ndb.nal.usda.gov/ndb/
Agricultural management			
Mineral fertilizers (N, P)	[31]	Fertilizer archives; Fertilizers	http://www.fao.org/faostat/en/#data/RA; http://www.fao.org/faostat/en/#data/EF
Area equipped for irrigation	[31]	Land use	http://www.fao.org/faostat/en/#data/RL
Social economic politic and environmental data			
Warfare	[34]	Armed Conflict and Intervention (ACI) datasets	http://www.systemicpeace.org/inscrdata.html
Weather	[35]	CRU TS v.3.23	https://crudata.uea.ac.uk/cru/data/hrg/
Proportion of cropland	[36]	Cropland and Pasture Area in 2000	http://www.earthstat.org/data-download/
Terrain elevation	[38]	Global Multi-resolution Terrain Elevation Data 2010	https://lta.cr.usgs.gov/GMTED2010
Soil map	[39]	FAO/UNESCO Soil Map of the World	http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/
Language diversity index	[40]	Ethnologue Language of the World	https://www.ethnologue.com/statistics/country

Extended Data Table 2 | Determinants of national caloric yield stability, mean and temporal variation

a

	Log caloric yield stability (μ/σ)			Log caloric yield SD (σ)			Log caloric mean yield (μ)		
	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*
AIC	781			789			363		
R2	0.37			0.42			0.65		
Group diversity	0.23 (0.028)	66.46	<.0001***	-0.11 (0.028)	13.91	0.0002***	0.12 (0.017)	50.17	<.0001***
sqrt(Irrigation)	0.088 (0.017)	27.04	<.0001***	-0.077 (0.017)	19.88	<.0001***	0.012 (0.011)	1.28	0.26
Precipitation instab.	-0.054 (0.0072)	56.94	<.0001***	0.026 (0.0072)	13.36	0.0003***	-0.028 (0.0044)	38.74	<.0001***
Temperature instab.	-0.0043 (0.00070)	38.21	<.0001***	0.0024 (0.00071)	11.07	0.001**	-0.0020 (0.00044)	20.77	<.0001***
Time	-0.047 (0.021)	5.13	0.024*	0.074 (0.021)	12.38	0.0005***	0.027 (0.013)	4.31	0.039*
sqrt(N use intensity)	0.019 (0.0085)	4.99	0.026*	0.099 (0.0086)	133.54	<.0001***	0.12 (0.0053)	503.07	<.0001***
Warfare	0.015 (0.018)	0.72	0.40	-0.036 (0.018)	4.03	0.05	-0.021 (0.011)	3.62	0.058

b

	Log caloric yield stability (μ/σ)			Log caloric yield SD (σ)			Log caloric mean yield (μ)		
	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*
AIC	812			781			408		
R2	0.32			0.43			0.61		
Species diversity	0.045 (0.0079)	32.60	<.0001***	-0.036 (0.0077)	22.42	<.0001***	0.0091 (0.0050)	3.28	0.071
sqrt(Irrigation)	0.078 (0.018)	18.46	<.0001***	-0.063 (0.018)	12.74	0.0004***	0.015 (0.011)	1.83	0.18
Precipitation instab.	-0.053 (0.0074)	51.68	<.0001***	0.025 (0.0072)	12.47	0.0005***	-0.028 (0.0047)	36.08	<.0001***
Temperature instab.	-0.0059 (0.00071)	69.41	<.0001***	0.0032 (0.00069)	21.86	<.0001***	-0.0027 (0.00045)	36.80	<.0001***
Time	-0.042 (0.022)	3.76	0.053	0.080 (0.021)	14.57	0.0002***	0.038 (0.014)	7.67	0.0059**
sqrt(N use intensity)	0.016 (0.015)	3.14	0.077	0.098 (0.0085)	134.92	<.0001***	0.11 (0.0055)	424.90	<.0001***
Warfare	0.0059 (0.018)	0.10	0.75	-0.030 (0.018)	2.80	0.095	-0.024 (0.011)	4.23	0.04*

a, **b**, Results for multiple linear regression models using non-standardized predictor variables. **a**, Results of a regression using effective crop group diversity ($n = 437$). **b**, Results of a regression using effective crop species diversity ($n = 437$). AIC, Akaike information criterion; R2, Spearman correlation coefficient; SE, standard error. Yield stability, μ and σ were log-transformed and the rate of nitrogen fertilization and irrigation were square-root (sqrt)-transformed. $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

Extended Data Table 3 | Robustness checks of models testing the crop diversity–stability relationship

a

	Log caloric yield stability (μ/σ)			Log caloric yield SD (σ)			Log caloric mean yield (μ)		
	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*
AIC	907			1022			840		
R^2	0.17			0.09			0.009		
Group diversity	0.28 (0.030)	91.83	<.0001***	-0.22 (0.034)	43.43	<.0001***	0.06 (0.028)	4.99	0.03*

b

	Log caloric yield stability (μ/σ)			Log caloric yield SD (σ)			Log caloric mean yield (μ)		
AIC	955			1046			843		
R^2	0.07			0.04			0.003		
Species diversity	0.051 (0.0085)	36.74	<.0001***	-0.040 (0.0094)	17.66	<.0001***	0.012 (0.0075)	2.53	0.11

c

	Log caloric yield stability (μ/σ)		
	Estimate (SE)	*F*	*P-value*
AIC	703		
R2	0.47		
Group diversity	0.27 (0.034)	64.44	<.0001***
sqrt(Irrigation)	0.093 (0.023)	15.96	<.0001***
Precipitation instab.	-0.039 (0.0079)	24.22	<.0001***
Temperature instab.	-0.0034 (0.00085)	16.06	<.0001***
Time	-0.040 (0.021)	3.73	0.054
sqrt(N use intensity)	0.0048 (0.012)	0.17	0.68
Warfare	0.0012 (0.018)	0.004	0.95
Geographic regions		5.70	<.0001***
Trade involvement		2.94	0.033*
Elevation range	-0.000013 (0.000025)	0.26	0.63
Soil diversity	-0.12 (0.061)	3.63	0.057
Cultural diversity	0.27 (0.15)	3.51	0.062
SOC	0.042 (0.024)	2.98	0.085
log(Country area)	0.27 (0.034)	5.62	0.018*

d

	Log caloric yield stability (μ/σ)		
	Estimate (SE)	*F*	*P-value*
AIC	737		
R2	0.42		
Species diversity	0.051 (0.0097)	27.99	<.0001***
sqrt(Irrigation)	0.089 (0.025)	12.89	0.0004***
Precipitation instab.	-0.046 (0.0081)	31.78	<.0001***
Temperature instab.	-0.0045 (0.00087)	27.14	<.0001***
Time	-0.030 (0.022)	1.94	0.16
sqrt(N use intensity)	-0.0030 (0.012)	0.061	0.81
Warfare	0.0025 (0.0019)	0.017	0.90
Geographic regions		5.37	<.0001***
Trade involvement		1.92	0.13
Elevation range	-0.000014 (0.000027)	0.27	0.61
Soil diversity	-0.13 (0.065)	4.04	0.05
Cultural diversity	0.17 (0.115)	1.19	0.28
SOC	0.058 (0.025)	5.27	0.02*
log(Country area)	0.040 (0.031)	1.67	0.20

a, **b**, Results for simple linear regression models using only non-standardized effective crop group diversity ($n = 437$) (**a**) and effective crop species diversity (**b**). **c**, **d**, Results show a complete model including the most important predictors of national yield stability as well as additional predictors. Yield stability was log-transformed and the rate of nitrogen fertilization, irrigation and country area were square-root-transformed. *$P < 0.05$; ***$P < 0.001$.

Extended Data Table 4 | Robustness checks for data quality

a

	Log caloric yield stability (μ/σ)			**Log caloric yield SD (σ)**			**Log caloric mean yield (μ)**		
	Estimate (SE)	***F***	***P-value***	**Estimate (SE)**	***F***	***P-value***	**Estimate (SE)**	***F***	***P-value***
AIC	**702**			**675**			**339**		
R2	0,33			0,42			0,61		
Species diversity	0.043 (0.0087)	24,57	<.0001***	-0.032 (0.0084)	14,29	0.0002***	0.011 (0.0054)	4,37	0.037*
sqrt(Irrigation)	0.071 (0.019)	14,28	0.0002***	-0.071 (0.018)	15,14	0.0001***	0.00042 (0.012)	0,00	0.97
Precipitation instab.	-0.057 (0.0081)	48,99	<.0001***	0.027 (0.0078)	11,87	0.0006***	-0.030 (0.0050)	34,49	<.0001***
Temperature instab.	-0.0061 (0.00074)	67,90	<.0001***	0.0035 (0.00071)	23,67	<.0001***	-0.0026 (0.00046)	32,09	<.0001***
Time	-0.023 (0.023)	1,03	0.31	0.066 (0.022)	8,98	0.0029**	0.043 (0.014)	9,04	0.0028**
sqrt(N use intensity)	0.019 (0.0091)	4,33	0.04*	0.092 (0.0088)	109,68	<.0001***	0.11 (0.0057)	380,14	<.0001***
Warfare	0.011 (0.019)	0,34	0.56	-0.034 (0.019)	3,27	0,071	-0.023 (0.012)	3,47	0.063
Proportion of estimated production data	-0.023 (0.74)	1,89	0.17	0.21 (0.72)	0,09	0,77	-0.81 (0.47)	3,01	0,084

b

	Log caloric yield stability (μ/σ)			**Log caloric yield SD (σ)**			**Log caloric mean yield (μ)**		
	Estimate (SE)	***F***	***P-value***	**Estimate (SE)**	***F***	***P-value***	**Estimate (SE)**	***F***	***P-value***
AIC	654			635			-34		
R2	0,73			0,75			0,96		
Fixed effects									
Species diversity	0.042 (0.013)	10,66	0.001**	-0.037 (0.012)	9,38	0.0026**	0.0010 (0.0062)	0,03	0.87
sqrt(Irrigation)	0.079 (0.029)	7,36	0.0075**	-0.058 (0.027)	4,41	0.038*	0.050 (0.015)	10,47	0.0013**
Precipitation instab.	-0.038 (0.0089)	17,77	<.0001***	0.025 (0.0087)	8,03	0.0048**	-0.0049 (0.0034)	2,10	0.15
Temperature instab.	-0.0032 (0.00076)	16,76	<.0001***	0.0021 (0.00077)	7,31	0.0072**	-0.00083 (0.00029)	8,25	0.0043**
Time	-0.012 (0.019)	0,42	0.52	0.076 (0.018)	17,20	<.0001***	0.077 (0.0075)	104,59	<.0001***
sqrt(N use intensity)	0.0087 (0.012)	0,51	0.48	0.079 (0.012)	45,41	<.0001***	0.061 (0.0051)	141,99	<.0001***
Warfare	-0.022 (0.019)	1,35	0.25	0.0099 (0.018)	0,29	0,59	-0.0061 (0.0066)	0,85	0.36
Proportion of estimated production data	-1.11 (0.71)	2,40	0.12	0.89 (0.70)	1,61	0,2	0.0057 (0.26)	0,0005	0,98
Variance component									
Country	0.22 (0.046)			0.18 (0.039)			0.17 (0.028)		

Robustness checks performed after exclusion of 68 decadal national stability results for which FAO-estimated harvest data were greater than 20% (Methods, $n = 437$). **a**, **b**, Results for simple linear regression models (**a**) and mixed-effect models using country as a random effect (**b**) and using only non-standardized variables. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

Extended Data Table 5 | Influence of crop diversity and mean weather on national caloric yield stability, mean and temporal variation

a

	Log caloric yield stability (μ/σ)			Log caloric yield SD (σ)			Log caloric mean yield (μ)		
	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*
AIC	811			802			280		
R2	0.33			0.4			0.71		
Group diversity	0.18 (0.031)	32.21	<.0001***	-0.099 (0.031)	10.43	0.0013**	0.077 (0.017)	20.6	<.0001***
sqrt(Irrigation)	0.093 (0.018)	27.37	<.0001***	-0.097 (0.018)	14.7	0.0001***	0.025 (0.0097)	6.9	0.0089**
Mean precipitation	0.0057 (0.00071)	63.13	<.0001***	-0.00050 (0.00071)	0.5	0.48	0.0052 (0.00039)	176.76	<.0001***
Mean precipitation^2	-0.000025 (0.0000057)	19.98	<.0001***	0.0000036 (0.0000056)	0.4	0.53	0.000022 (0.00000031)	49.78	<.0001***
Mean temperature	0.0015 (0.0070)	0.046	0.83	-0.023 (0.0069)	10.85	0.0011**	-0.021 (0.0038)	31.33	<.0001***
Time	-0.029 (0.022)	1.76	0.19	0.079 (0.022)	13.2	0.0003***	0.050 (0.012)	17.4	<.0001***
sqrt(N use intensity)	0.0045 (0.010)	0.19	0.66	0.098 (0.010)	78.12	<.0001***	0.094 (0.0056)	285.05	<.0001***
Warfare	0.021 (0.019)	1.24	0.27	-0.042 (0.018)	5.26	0.022	-0.022 (0.010)	4.54	0.03*

b

	Log caloric yield stability (μ/σ)			Log caloric yield SD (σ)			Log caloric mean yield (μ)		
	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*
AIC	814			790			299		
R2	0.32			0.42			0.7		
Species diversity	0.044 (0.0082)	29.14	<.0001***	-0.039 (0.0080)	23.63	<.0001***	0.0055 (0.0045)	1.44	0.23
sqrt(Irrigation)	0.084 (0.018)	21.11	<.0001***	-0.054 (0.018)	9.17	0.0026**	0.030 (0.010)	8.79	0.0032*
Mean precipitation	0.0068 (0.00068)	100.25	<.0001***	-0.0011 (0.00066)	2.65	0.10	0.0057 (0.00038)	230.4	<.0001***
Mean precipitation^2	-0.000028 (0.0000056)	25.23	<.0001***	0.0000030 (0.00066)	0.3	0.58	0.000025 (0.00000031)	65.35	<.0001***
Mean temperature	0.0068 (0.0070)	0.96	0.35	-0.026 (0.0068)	15.11	0.0001***	-0.020 (0.0039)	25.55	<.0001***
Time	-0.031 (0.022)	1.98	0.16	0.087 (0.021)	16.45	<.0001***	0.056 (0.012)	20.94	<.0001***
sqrt(N use intensity)	0.0038 (0.010)	0.14	0.71	0.088 (0.0099)	78.08	<.0001***	0.091 (0.0057)	261.06	<.0001***
Warfare	0.0084 (0.019)	0.2	0.65	-0.032 (0.018)	3.15	0.077	-0.024 (0.010)	5.3	0.02*

Results for multiple linear regression models using non-standardized predictor variables ($n = 437$). **a**, A regression using effective crop group diversity. **b**, A regression using effective crop species diversity. Yield stability, μ and σ were log-transformed and the rate of nitrogen fertilization and irrigation were square-root-transformed. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

Extended Data Table 6 | Determinants of caloric yield stability, mean and temporal variation of geographical regions

a

	Log caloric yield stability (μ/σ)			Log caloric yield SD (σ)			Log caloric mean yield (μ)		
	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*
AIC	63			65			-50		
R2	0.81			0.82			0.99		
Group diversity	1.14 (0.51)	5.03	0.039*	-1.15 (0.52)	9.55	0.04*	-0.016 (0.076)	0.043	0.84
Irrigation	0.063 (0.059)	1.12	0.30	-0.049 (0.061)	8.22	0.43	0.014 (0.0089)	2.42	0.14
Precipitation instab.	-0.0026 (0.019)	0.019	0.89	-0.0020 (0.019)	13.45	0.92	-0.0046 (0.0028)	2.68	0.12
Temperature instab.	0.0033 (0.0040)	0.68	0.42	-0.0028 (0.0041)	8.48	0.50	0.00047 (0.00060)	0.63	0.44
Time	-0.019 (0.10)	3.15	0.09	0.28 (0.11)	9.44	0.02*	0.099 (0.016)	39.74	<.0001***
N use intensity	-6.99 (7.019)	0.99	0.33	9.41 (7.23)	84.48	0.21	2.42 (1.05)	5.26	0.034*
Warfare	0.090 (0.17)	0.27	0.61	-0.068 (0.18)	2.13	0.71	0.023 (0.026)	0.76	0.29
Geographic regions		0.53	0.75		2.14	0.85		49.87	<.0001***
Africa	-0.57 (0.062)			0.19 (0.64)			-0.38 (0.0093)	17.87	
Asia	-0.50 (1.17)			0.21 (1.20)			-0.29 (0.18)		
Europe	0.16 (0.50)			0.08 (0.52)			0.24 (0.075)		
Latin America/Caribbean	-0.41 (0.59)			0.60 (0.61)			0.18 (0.089)		
North America	0.67 (0.55)			-0.30 (0.56)			0.37 (0.082)		

b

	Log caloric yield stability (μ/σ)			Log caloric yield SD (σ)			Log caloric mean yield (μ)		
	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*
AIC	50			49			-55		
R2	0.87			0.90			0.99		
Species diversity	0.29 (0.071)	16.98	0.0007***	-0.031 (0.069)	20.61	0.0003***	-0.0022 (0.012)	3.25	0.09
Irrigation	-0.022 (0.052)	0.17	0.68	0.042 (0.051)	0.68	0.42	0.0020 (0.0089)	5.17	0.04*
Precipitation instab.	-0.023 (0.016)	2.27	0.15	0.020 (0.014)	1.79	0.20	-0.0031 (0.0027)	1.36	0.26
Temperature instab.	0.00092 (0.00031)	0.08	0.77	-0.00036 (0.0031)	0.014	0.91	0.00055 (0.00054)	1.05	0.32
Time	-0.098 (0.067)	2.09	0.17	0.20 (0.066)	9.10	0.0078**	0.10 (0.011)	76.53	<.0001***
N use intensity	-1.72 (5.63)	0.093	0.76	3.87 (5.49)	0.50	0.49	2.17 (0.96)	5.06	0.04*
Warfare	0.071 (0.14)	0.26	0.62	-0.047 (0.14)	0.12	0.73	0.024 (0.024)	1.0033	0.33
Geographic regions		5.054	0.0051**		3.62	0.02*		29.45	<.0001***
Africa	-2.92 (0.88)			2.78 (0.86)			-0.15 (0.15)		
Asia	-0.063 (0.094)			-0.24 (0.91)			-0.31 (0.16)		
Europe	0.25 (0.40)			-0.015 (0.39)			0.24 (0.069)		
Latin America/Caribbean	0.34 (0.29)			-0.15 (0.28)			0.19 (0.049)		
North America	1.15 (0.44)			-0.86 (0.43)			0.28 (0.076)		

Results for multiple linear regression models using non-standardized predictor variables aggregated across six world geographical regions (n = 30). **a**, A regression using effective crop group diversity. **b**, A regression using effective crop species diversity. Stability, μ and σ of caloric yield were log-transformed. Oceania is the reference region to which results for every other region is compared.
$*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

Extended Data Table 7 | Determinants of national economic yield stability, mean and temporal variation

a

	Log economic yield stability (μ/σ)			Log economic yield SD (σ)			Log economic mean yield (μ)		
	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*
AIC	753			877			310		
R2	0.29			0.44			0.78		
Group diversity	0.12 (0.027)	19.12	<.0001***	0.19 (0.031)	37.06	<.0001***	0.30 (0.016)	348.61	<.0001***
sqrt(Irrigation)	0.11 (0.016)	49.5	<.0001***	-0.015 (0.019)	0.65	0.42	0.099 (0.0098)	100.88	<.0001***
Precipitation instab.	-0.052 (0.0068)	59.73	<.0001***	0.047 (0.0078)	35.83	<.0001***	-0.0057 (0.0041)	1.89	0.17
Temperature instab.	-0.0027 (0.00067)	15.85	<.0001***	0.0026 (0.00077)	11.38	0.0008***	-0.000073 (0.00041)	0.033	0.86
Time	-0.031 (0.020)	2.54	0.11	0.032 (0.023)	1.97	0.16	0.00083 (0.012)	0.0048	0.94
sqrt(N use intensity)	0.0048 (0.0080)	0.36	0.55	0.11 (0.0092)	133.56	<.0001***	0.11 (0.0049)	520.1	<.0001***
Warfare	0.031 (0.016)	3.66	0.056	-0.066 (0.018)	12.77	0.0004***	-0.035 (0.0098)	12.88	0.0004***

b

	Log economic yield stability (μ/σ)			Log economic yield SD (σ)			Log economic mean yield (μ)		
	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*	Estimate (SE)	*F*	*P-value*
AIC	761			896			451		
R2	0.28			0.41			0.69		
Species diversity	0.025 (0.0073)	12.21	0.0005***	0.034 (0.0085)	16.46	<.0001***	0.060 (0.0051)	135.26	<.0001***
sqrt(Irrigation)	0.11 (0.017)	41.64	<.0001***	-0.021 (0.019)	1.16	0.28	0.087 (0.012)	54.00	<.0001***
Precipitation instab.	-0.052 (0.0068)	57.79	<.0001***	0.047 (0.0080)	34.44	<.0001***	-0.0051 (0.0048)	1.11	0.29
Temperature instab.	-0.0035 (0.00066)	28.59	<.0001***	0.0013 (0.00077)	2.74	0.099	-0.0022 (0.00046)	23.38	<.0001***
Time	-0.030 (0.029)	2.23	0.14	0.038 (0.023)	2.63	0.11	0.0083 (0.014)	0.34	0.56
sqrt(N use intensity)	0.0036 (0.0081)	0.20	0.65	0.10 (0.0094)	121.70	<.0001***	0.11 (0.0057)	354.19	<.0001***
Warfare	0.024 (0.00166)	2.23	0.14	-0.076 (0.019)	16.12	<.0001***	-0.051 (0.011)	20.19	<.0001***

Results for multiple linear regression models using non-standardized predictor variables ($n = 437$). **a**, A regression using effective crop group diversity. **b**, A regression using effective crop species diversity. Stability, μ and σ of economic yield were log-transformed and the rate of nitrogen fertilization and irrigation were square-root-transformed. $^{***}P < 0.001$.

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Reporting Summary

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Statistical parameters

When statistical analyses are reported, confirm that the following items are present in the relevant location (e.g. figure legend, table legend, main text, or Methods section).

n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	An indication of whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
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☐	☒	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
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☒	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated
☐	☒	Clearly defined error bars *State explicitly what error bars represent (e.g. SD, SE, CI)*

Our web collection on statistics for biologists may be useful.

Software and code

Policy information about availability of computer code

Data collection	*Provide a description of all commercial, open source and custom code used to collect the data in this study, specifying the version used OR state that no software was used.*
Data analysis	JMP Pro version 12.0.1 (statistical software used for modeling) ; QGIS 2.18 (open source software for geostatistical treatment)

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Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:
- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

The sources of all data used in this study appear in the main text, are referenced in the Methods section and all data are accessible at the URL’s provided in the Extended Data Table 1

Field-specific reporting

Please select the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/authors/policies/ReportingSummary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We test the crop diversity-stability relationship using 50 years (1961-2010) of annual harvest data on 176 crop species for each of 91 populous nations by analyzing the dependence of the temporal stability of crop yield on effective crop species and group diversity. To do this, we divided the 50-year data record into 5 decade-long intervals, and calculated yield stability for each interval and nation. We used linear regression models to test for this dependence. Models include time, growing season precipitation and temperature or their temporal stability, rates of fertilization and irrigation and warfare as covariates. We performed additional analyses including an index of data quality as an additional variable in our analyses.
Research sample	The 91 nations analyzed are the globally most populous nations for which temporally complete and high-quality data sets are available. All the data used in our study are accessible online, the source appear in the main text and URL are provided in the Methods section of the manuscript and in a table in the Extended Data Table 1. For each nation and each year, agricultural data (area harvested and production for 176 individual crop species, rate of mineral fertilization, area fitted with irrigation equipment) were obtained from the FAOSTAT database. We also used a dataset from the Center for Systematic Peace: the magnitude of Major Episodes of Political Violence, from which we derived an indicator of warfare. We obtained global gridded climatic data from the Climate Research Unit of the University of Anglia (CRU TS v.3.23).
Sampling strategy	We used the 91 most populous nations because, as mentioned above, these nations are highly representative of global trends, have better data availability, quality and because use of small nations would undue weight to them.
Data collection	Dr. Delphine Renard searched for, downloaded, assembled and verified all data used in our analyses. Dr. David Tilman reviewed and double-checked the data, and independently repeated statistical analyses, including doing additional analyses to assure that reported results were highly robust.
Timing and spatial scale	Data collection for each of the 91 nations studied started in 2016. Updated data on fertilizers, irrigation and warfare were downloaded in January 2018.
Data exclusions	From an initial sample of 100 nations, we removed five nations for which at least 20% of their data on area harvested or production had to be estimated by the FAO. Because Ireland, New Zealand and Netherlands use much of their fertilizer on pastures rather than croplands, and because we could not find annual quantitative data on the amounts so used, they were also excluded from the models. Egypt, which has 100% of cropland equipped with irrigation for the five decades was also removed from the models.
Reproducibility	Not applicable to our study
Randomization	Not applicable to our study as it is not experimental
Blinding	Not applicable to our study

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

Materials & experimental systems

n/a	Involved in the study
☒	☐ Unique biological materials
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☒	☐ Animals and other organisms
☒	☐ Human research participants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging