The International Treaty
ON PLANT GENETIC RESOURCES FOR FOOD AND AGRICULTURE

Research Study 8

Estimation of countries' interdependence in plant genetic resources provisioning national food supplies and production systems

Colin K. Khoury, Harold A. Achicanoy, Anne D. Bjorkman, Carlos Navarro-Racines,
Luigi Guarino, Ximena Flores-Palacios, Johannes M.M. Engels, John H. Wiersema,
Hannes Dempewolf, Julian Ramírez-Villegas, Nora P. Castañeda-Álvarez, Cary Fowler,
Andy Jarvis, Loren H. Rieseberg, and Paul C. Struik

www.planttreaty.org

Authors:
Colin K. Khoury, International Center for Tropical Agriculture, Cali, Colombia; Centre for Crop Systems Analysis, Wageningen University, Wageningen, The Netherlands
Harold A. Achicanoy, International Center for Tropical Agriculture, Cali, Colombia
Anne D. Bjorkman, German Centre for Integrative Biodiversity Research, Leipzig, Germany
Carlos Navarro-Racines, International Center for Tropical Agriculture, Cali, Colombia; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Cali, Colombia
Luigi Guarino, Global Crop Diversity Trust, Bonn, Germany
Ximena Flores-Palacios, Auckland University of Technology, Auckland, New Zealand
Johannes M.M. Engels, Bioversity International, Maccarese, Italy
John H. Wiersema, United States Department of Agriculture, Agricultural Research Service, National Germplasm Research Laboratory, Beltsville, MD, USA
Hannes Dempewolf, Global Crop Diversity Trust, Bonn, Germany
Julian Ramírez-Villegas, International Center for Tropical Agriculture, Cali, Colombia; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Cali, Colombia; School of Earth and Environment, University of Leeds, Leeds, UK
Nora P. Castañeda-Álvarez, International Center for Tropical Agriculture, Cali, Colombia; School of Biosciences, University of Birmingham, Edgbaston, Birmingham, UK
Cary Fowler, Global Crop Diversity Trust, Bonn, Germany
Andy Jarvis, International Center for Tropical Agriculture, Cali, Colombia; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Cali, Colombia
Loren H. Rieseberg, The Biodiversity Research Centre, University of British Columbia, Vancouver, BC, Canada; Department of Botany, University of British Columbia, Vancouver, BC, Canada; Department of Biology, Indiana University, Bloomington, IN, USA
Paul C. Struik, Centre for Crop Systems Analysis, Wageningen University, Wageningen, The Netherlands

Corresponding author: Colin K. Khoury: c.khoury@cgiar.org

Following Resolution 2/2013, the Secretary of the International Treaty invited Contracting Parties, Non-Contracting Parties, stakeholder groups and international organizations in February 2014 to make available relevant information related to the work of the *Ad Hoc* Open-ended Working Group to Enhance the Functioning of the Multilateral System of Access and Benefit Sharing. On April 2014, the Director General of the International Center for Tropical Agriculture (CIAT), Ruben Echeverría, informed the Secretary that a number of international institutions and research universities were conducting an analysis on the quantification of interdependence in the plant genetic resources underpinning national food supplies and expressed that their intention was to make the analysis available to the Working Group to inform policy discussions. For more information: http://www.planttreaty.org/sites/default/files/OWG-EFMLS1-14-I03e.pdf

Executive Summary

1. This analysis provides an estimation of the degree of interdependence among countries in regard to plant genetic resources, i.e., the genetic diversity that is employed through crop improvement to enhance the productivity, the resilience, and ultimately the security of food systems.

2. Countries' interdependence in plant genetic resources represents one of the key arguments for the Multilateral System of Access and Benefit Sharing (MLS) of the International Treaty on Plant Genetic Resources for Food and Agriculture (Plant Treaty). A relatively narrow analysis providing an estimation of this interdependence served as an important contribution during preliminary negotiations of the Plant Treaty, over 15 years ago. The present document provides a fully updated estimation of interdependence among countries, with major enhancements in regard to the breadth and depth of the analysis, and using powerful visualization tools to display the results. Key enhancements include: (a) an estimation of countries' interdependence in plant genetic resources not only in regard to calories, but also protein, fat, and total weight in national food supplies; (b) an analysis of countries' interdependence in regard to the plant genetic resources underpinning national agricultural production systems, measured in production quantity, harvested area, and production value; (c) an assessment of change over the past 50 years in countries' interdependence in these food supply and production metrics, and (d) an analysis of the relationship between interdependence and diversity in national food systems, as well as Gross Domestic Product (GDP). These analyses provide an indication of the degree to which international exchange is potentially necessary to access the plant genetic resources that underpin national food supplies and production systems, and therefore strengthen national food security and national economies.

3. Results of the analyses demonstrate that national food supplies and production systems are highly interdependent worldwide in regard to plant genetic resources. Countries strongly depend on crops whose genetic diversity originates largely outside their borders, both in their food supplies (65.8% dependence on crops of "foreign" primary regions of diversity for calories, 66.6% for protein, 73.7% for fat, and 68.7% for food weight as an average across countries worldwide) and in their production systems (71.0% for production quantity, 64.0% for harvested area, and 72.9% for production value). The global average of the degree of countries' dependence on "foreign" crops is 68.7% across food supply variables, 69.3% across production variables, and 69.0% across all variables for all countries.

4. Acknowledging variation across countries and across food supply and production metrics in the degree of dependence on crops of "foreign" primary regions of diversity, the results clearly demonstrate extensive interdependence worldwide, in all regions and on all continents, including in countries located in areas of high indigenous crop diversity. National dependence on "foreign" crops has increased over the past 50 years in concert with economic and agricultural development and the globalization of food systems. Dependence is positively correlated with diversity in food systems as well as with national GDP.

5. Global interdependence in plant genetic resources bolsters the rationale for considering this agricultural diversity as a public good, which should be proactively conserved and made available as freely as possible worldwide. The results particularly support the argument for the more comprehensive participation of countries in the MLS in order to enhance long term food security and economic growth, and for widening the scope of the diversity currently covered in Annex 1 of the Plant Treaty in order to consider all crops of present and future international importance.

Introduction

6. At its Fifth Session, the Governing Body of the International Treaty on Plant Genetic Resources for Food and Agriculture (Plant Treaty) established the *Ad Hoc* Open-Ended Working Group to Enhance the Functioning of the Multilateral System of Access and Benefit Sharing (MLS), through Resolution 2/2013, Implementation of the Funding Strategy of the International Treaty on Plant Genetic Resources for Food and Agriculture. The Working Group was charged with developing a range of measures for consideration and decision by the Governing Body at its Sixth Session that will increase user-based payments and contributions to the Benefit-Sharing Fund in a sustainable and predictable long-term manner, and enhance the functioning of the MLS by additional measures.

7. For this purpose, the Secretariat was charged with preparing a number of short, strategic preliminary studies, taking into account all available information of relevance to the interests of the Working Group. Among others, these studies were proposed to include an analysis of the factors that influence the willingness of stakeholder groups to make contributions to the enhancement of the MLS.

8. In response to a call by the Secretariat to encourage international organizations to make available information relevant to the Working Group, the International Center for Tropical Agriculture (CIAT), the Global Crop Diversity Trust, the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Bioversity International, the Agricultural Research Service of the United States Department of Agriculture (USDA-ARS), and a number of research universities, have prepared this "Estimation of countries' interdependence in plant genetic resources provisioning national food supplies and production systems."

9. This analysis provides an estimation of the degree of interdependence among countries in regard to plant genetic resources, i.e., the genetic diversity that is employed through crop improvement to enhance the productivity, the resilience, and ultimately the security of national food systems. The effort builds upon an earlier, relatively narrow in scope analysis[1] which served as an important contribution during preliminary negotiations of the Plant Treaty, over 15 years ago.

10. The present document provides a comprehensive and fully updated estimation of interdependence among countries, with major enhancements relative to the earlier study in regard to the breadth and depth of the analysis, and using powerful visualization tools to

display the results. Key enhancements include:

- a current estimation of countries' interdependence in plant genetic resources not only in regard to calories, but also to protein, fat, and total weight in national food supplies, analyzing 177 countries covering 98.5% of the world's population;
- a current estimation of countries' interdependence in regard to the plant genetic resources underpinning national agricultural production systems, measured in production quantity, harvested area, and production value, with a similar degree of geographic and world population coverage;
- an assessment of change in the past 50 years in countries' interdependence in these food supply and production metrics; and
- an analysis of the relationship between interdependence and diversity in national food systems, as well as Gross Domestic Product (GDP).

Context on plant genetic resources and interdependence among countries

11. Plant genetic resources are a cornerstone of food security, utilized as the building blocks of crop improvement by farmers and modern plant breeders alike. This crop genetic diversity is employed for breeding varieties that are adapted to biotic and abiotic stresses and are higher yielding. These resources also represent the palette from which food systems may be diversified.[2-7] The need for utilization of this genetic diversity to maintain or enhance crop productivity is likely only to grow given rising food demand and increasing constraints on the use of non-renewable agricultural inputs, limitations in further expansion of arable lands, soil degradation, and global climatic change.[8-12]

12. Crop genetic diversity is generated through natural processes of genetic mutation and recombination, and is further transformed through natural selection by environmental pressures, as well as through artificial selection by farmers and plant breeders. As genetic diversity from such processes accumulates over time, particularly high levels of variation are found where crops and their wild relatives have evolved over long periods, in specific geographic regions worldwide. A century ago, N. I. Vavilov described these "centres of origin," which included Central America and Mexico; parts of the Andes, Chile and Brazil-Paraguay; the Mediterranean; the Near East; Ethiopia; Central Asia; India; China; and Indo-Malaysia.[13-15] Since then, the number and boundaries of these centres have been debated, investigated and refined.[16-21] Here we use the term "primary regions of diversity" to describe these areas, which typically include the locations of the initial domestication of crops, encompass major geographic zones of varietal diversity generated since that time, and generally also include high species richness in related wild taxa.

13. New forms and combinations of crop genetic diversity may arise wherever farmers and plant breeders are active.[22-23] The spread of crops outside their centres of origin and their increasing contribution to the diets of diverse cultures in different regions[2] have therefore led to the development of "secondary centres of diversity," as well as novel genotypes arising outside of any such defined centres. Some weedy crop wild relative species have also

expanded in their distributions, taking advantage of increasing disturbance of natural habitats. While all crop genetic variation, regardless of geographic distribution, is of potential value to crop improvement, the wealth of diversity generated over time in the primary regions is considered to be the centrepiece of current and future crop improvement efforts due to its comparatively high values at allelic, genotypic, and species levels.[4,6,13,19]

Cassava, maize, groundnut and common bean originated in Latin America and have become staples in many countries of sub-Saharan Africa. Cassava, for example, is the crop with the highest production in sub-Saharan Africa, and is a major caloric source for 500 million people.[24] At the same time, indigenous African crops such as sorghum, oil palm and coffee are important contributors to the agriculture of other regions, including Latin America, and South and Southeast Asia.[25] The spread of food crops from their geographic origins continues in the present.[26] Modern diets are comprised of a mixture of food crops originating from all around the world, and this mixture is becoming increasingly homogeneous worldwide.[2]

14. Erosion of crop genetic diversity has occurred over the past century, particularly through the adoption of improved high-yielding crop varieties and substitute crop species and subsequent neglect of traditional varieties and crops, economic development and associated shifts in consumer demand, land use change and habitat destruction, and urbanization and the displacement of cultures associated with particular crops and varieties.[4,6-7,27-29] In the primary regions of diversity of some crops, only a fraction of the diversity once present is thought to still be found today in farmers' fields, e.g., in wheat varieties in parts of the Fertile Crescent.[6,22] Due to the loss of variation in regions of diversity, the world's genebanks originally established to make plant genetic resources readily available to breeders for crop improvement, have come to represent essential repositories for crop diversity conservation. A considerable portion of the world's remaining heritage of plant genetic resources, in particular of the major food staples, is likely now conserved exclusively in national, regional, and/or international genebanks.[4,6-7,30-31]

15. Thus, the long-term productivity and resilience of agriculture is dependent upon the conservation and availability of plant genetic resources, accessed either directly from regions of diversity or via genebanks.[4,6-7,30,32] Considerable further scientific and political efforts are required in order to maximize the potential contribution of this diversity to global food and nutrition security. These include: conserving remnant crop and wild relative diversity *in situ*, further collecting for safeguarding in genebanks *ex situ*, ensuring that genebanks are equipped to conserve and distribute these plant genetic resources over the long term, generating useful information regarding the diversity present within these resources, and improving access to this diversity for plant breeders and researchers.[4,6-7,30,33-34]

16. Current deficiencies in conservation and access to plant genetic resources may be abetted by a lack of thorough information on the significance of this diversity, and its geography, to food systems worldwide. Direct measures of exchange of plant genetic resources among countries are not historically available on the global scale, as neither tracking of collecting activities, nor the movement of samples from the world's genebanks, have been

comprehensively recorded or made available. Documentations of exchange in genetic resources held in trust for the global community by international genebanks, as well as samples distributed by the United States National Plant Germplasm System, have revealed increasing transfers internationally over time.[33,35-38] The value of individual genetic resources to commercial crop varieties is similarly sparsely recorded, although the contribution of breeding materials from increasingly diverse geographic backgrounds to the development of modern cultivars has been documented for a few major cereal and grain legume crops.[39-46] Perhaps most acutely, the subsequent economic, social, and food and nutrition security benefits derived from production of these crop varieties have not been well documented. While the new information mechanisms associated with the Plant Treaty hold promise in filling some critical gaps in this information in the coming years, a more general approach is currently needed to elucidate present and future needs for utilization of plant genetic resources in food systems worldwide, and to discuss implications in regard to conservation and access.

17. Here we contribute to information on the importance of the geography of plant genetic resources to food security by determining the degree to which the national food supplies (measured in calories, protein, fat, and food weight) and national production systems (measured in production quantity, harvested area, and production value) of countries worldwide are comprised of crops from all the different primary regions of crop diversity. In order to assess the level to which international collaboration is potentially necessary to access useful plant genetic resources, we estimate the degree of dependence of countries upon crops from primary regions of diversity other than their own (i.e., crops of "foreign" primary regions of diversity, or "foreign" crops), and determine change in this dependence over the past 50 years. We also analyze the relationship between dependence and diversity in national food systems, as well as Gross Domestic Product (GDP). Methods and limitations in regard to this analysis are described in full in Annex I of this document.

Results

Countries are highly interconnected in regard to the primary regions of diversity of crops important in their national food supplies and production systems

18. Primary regions of diversity of agricultural crops were identified across the tropics and subtropics, extending into temperate regions in both hemispheres (Figure 1, Supplementary Figure 1). The food supplies and production systems of countries worldwide were found to be comprised of a wide range of crops from diverse geographic backgrounds, indicating a thoroughly interconnected global food system in regard to the geographic origins of crop genetic diversity (Figure 2, Supplementary Figure 2). The evident widespread importance in global food supplies particularly of major crops such as wheat, rice, sugarcane, maize, soybean, potatoes, barley, oil palm, beans, tomatoes, bananas & plantains, and sugar beet, among others, lead to particular significance of key primary regions of diversity, including West, Central, South, Southeast, and East Asia, the South and East Mediterranean, West and Central Africa, Central America and Mexico, Andean and tropical South America, and southern Europe (Figure 2 and Supplementary Figures 2-3). Cassava, rape & mustard, groundnut, grapes, apples, alfalfa, sorghum, and millets were among other crops of particular international importance for one or more food supply and/or production variables.

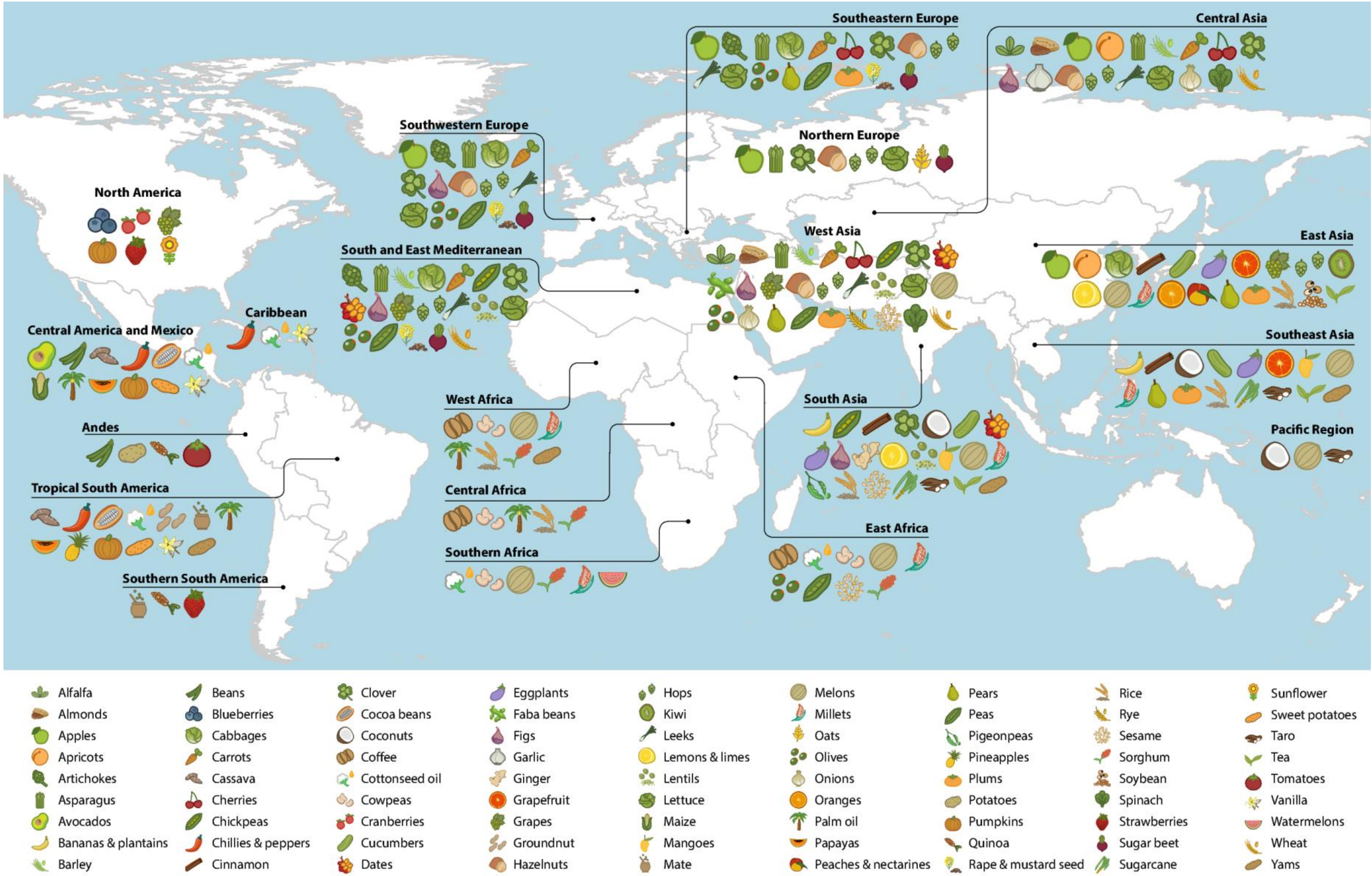

Figure 1. Primary regions of diversity of major agricultural crops worldwide. See Supplementary Table 6 for a list of primary regions for all assessed crop commodities.

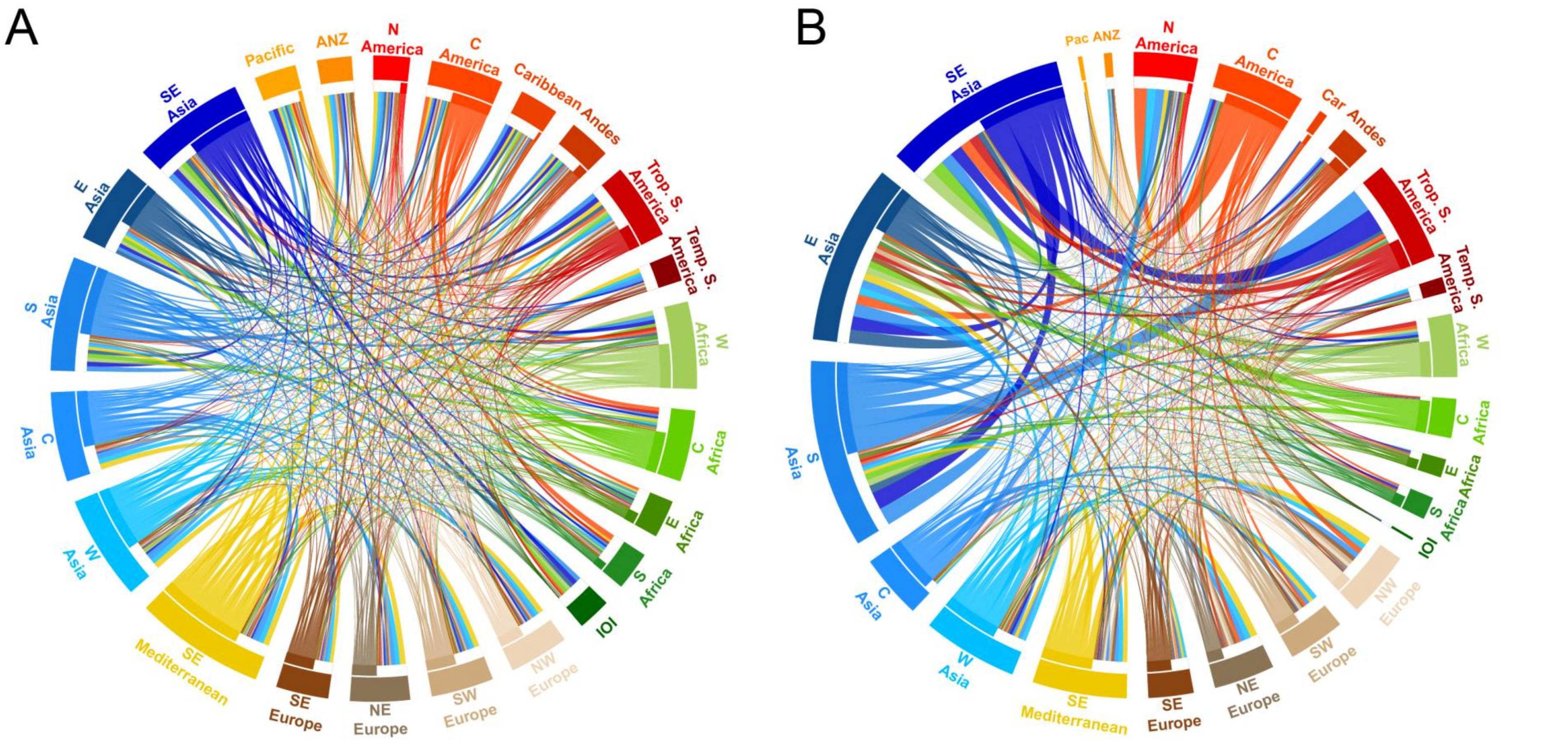

Figure 2. Circular plots displaying the primary regions of diversity of crops comprising (A) calories in national food supplies, and (B) production quantity in national production systems. The direction of the contribution is indicated by both the origin region's color and a gap between the connecting line and the destination region's segment. The magnitude of contribution is indicated by the width of the connecting line. Because the line width is nonlinearly adapted to the curvature, it corresponds to the contribution size only at the start and end points. As an example, (B) clearly displays the importance of crops of South and Southeast Asian primary regions of diversity, namely sugarcane, rice, and bananas & plantains, in production in tropical South America. For recipient data, regional caloric food supply values (kcal/capita/day) were formed by deriving a weighted average across countries comprising each region, with national values weighted by population. Regional production quantity values were formed by summing values across countries. For countries within regions, see Supplementary Table 7. Region names are shortened in the figures; IOI = Indian Ocean Islands, ANZ = Australia and New Zealand, and C. America = Central America and Mexico; and in production quantity only, Car = Caribbean, and Pac = Tropical Pacific Region. See Supplementary Figure 2 for circular plots for all measured food supply and production variables.

Countries highly depend on crops whose genetic diversity largely originates from outside their borders

19. Mean dependence across all countries on crops of "foreign" primary regions of diversity in food supplies was (mean ± SD) 65.8% ± 1.8 for calories, 66.6% ± 2.1 for protein, 73.7% ± 1.6 for fat, and 68.7% ± 1.4 for food weight. Mean dependence in production systems was 71.0% ± 1.8 for production quantity, 64.0% ± 2.2 for harvested area, and 72.9% ± 1.9 for production value. The combined mean dependence across food supply variables was estimated at 68.7%, across production systems at 69.3%, and across food systems worldwide (i.e., both food supplies and production systems, across all countries and all variables) at 69.0% (see Supplementary Tables 1-2 for dependence metrics per country).

20. Dependence upon crops of "foreign" primary regions of diversity in national food supplies and production systems was highest (i.e., up to 100%) in those countries geographically isolated from and/or located at great distance from the primary regions of diversity of major staple crops (Figures 3-4, Supplementary Tables 1-2). This includes Australia and New Zealand, the Indian Ocean Islands, the Caribbean, southern South America, North America, southern Africa, and northern Europe. These countries are generally in temperate climates, although tropical islands and some continental tropical regions, such as Central Africa, also demonstrated very high levels of dependence for most variables.

21. Conversely, dependence upon crops of "foreign" primary regions of diversity was lowest in countries located within the primary regions of diversity of major crops, and where traditional staples are still cultivated and consumed, such as Southeast Asia, the South and East Mediterranean, South Asia, Central Asia, West Asia, and West Africa (Figures 3-4, Supplementary Tables 1-2). The lowest levels of dependence were found in countries with food systems dominated by a limited number of traditional staples such as rice, wheat, yams, sorghum, and millets. Island nations predominantly dependent upon native crops for fat, such as coconut in the tropical Pacific Region, and countries with extreme agro-ecological conditions limiting national production to the cultivation of a select number of native crops (e.g., dates in the United Arab Emirates and other arid nations of West Asia) also exhibited very low levels of dependence for relevant food supply or production metrics. In such extreme cases, though, low dependence was generally evident in only one or a few food supplies or production metrics, while other variables exhibited much higher dependence.

22. Although food supplies and production systems variables were highly correlated in degree of dependence (Supplementary Figures 4-5), variation was also visible across variables, with highest overall dependence evident in fat, production value, production quantity, and food weight (Supplementary Tables 1-2). Considerable variation in dependence was found within geographic areas, e.g., ranging from 48.2% ± 1.6 for calories in Mexico, to 86.5% ± 1.4 in Panama, within the Central America and Mexico region. Large variation in dependence in production systems was also found within regions, e.g., ranging from 25.7% ± 3.5 for production value in the Philippines, to 94.1% ± 1.1 for Malaysia, within the Southeast Asia region. Countries with very high dependence for such production variables were exemplified by the presence of extensive production systems dedicated to a limited number of high value "foreign" commodity crops, such as oil palm in Malaysia.

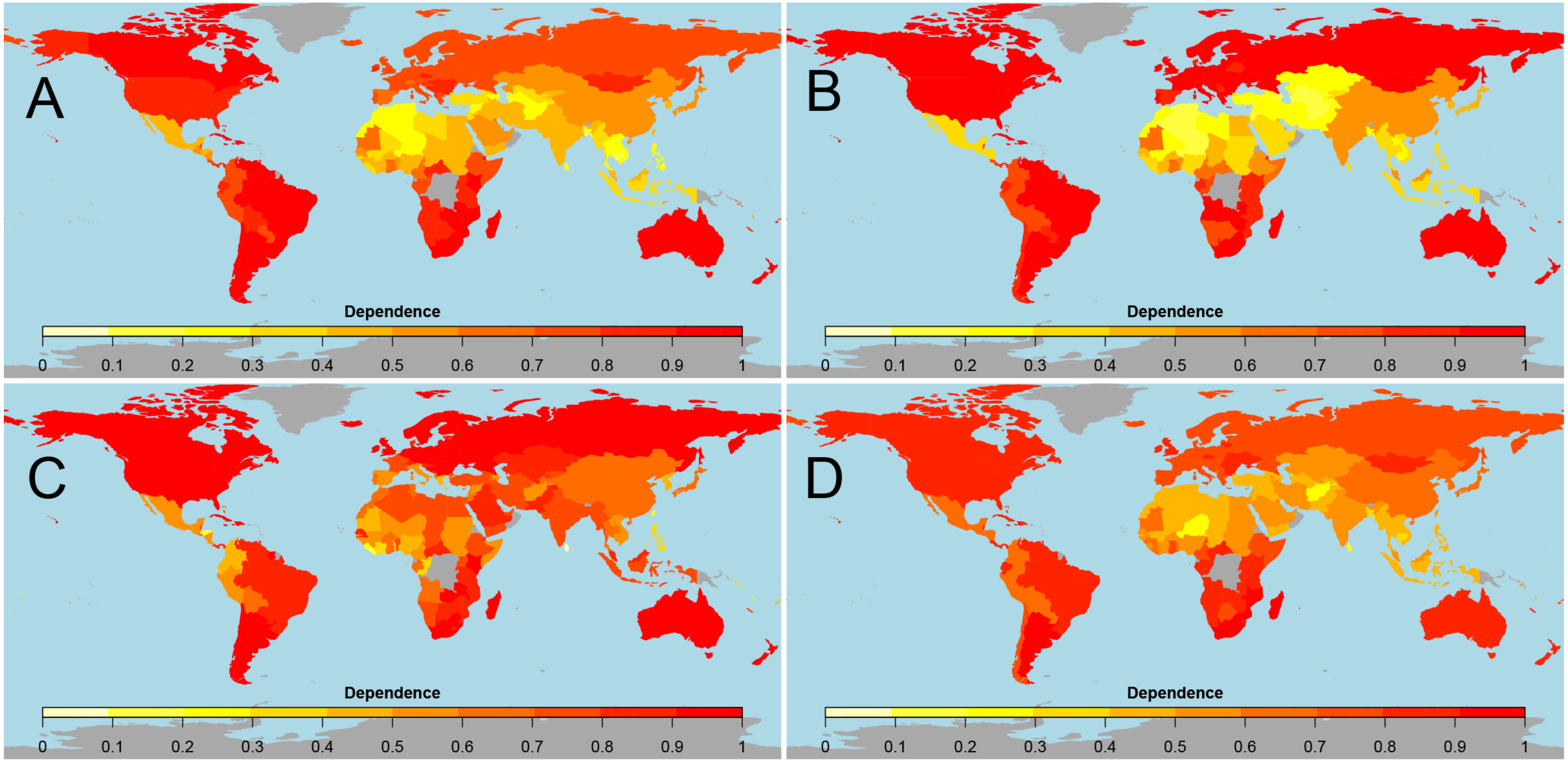

Figure 3. Degree of dependence per country on crops whose genetic diversity originates outside their borders in national food supplies [(A) calories, (B) protein, (C) fat, and (D) food weight] as a modeled mean between minimum and maximum dependence per country, 2009-2011. Dependence scale is degree of dependence (1 = completely dependent). As examples, (A) demonstrates that Canada (dark red) is highly dependent on "foreign" crops in terms of their contribution to calories in national food supplies (estimated value is 92.5% ± 2.6), and (B) shows that Zimbabwe (dark red) is highly dependent in terms of their contribution to protein (estimated value is 92.0% ± 0.6).

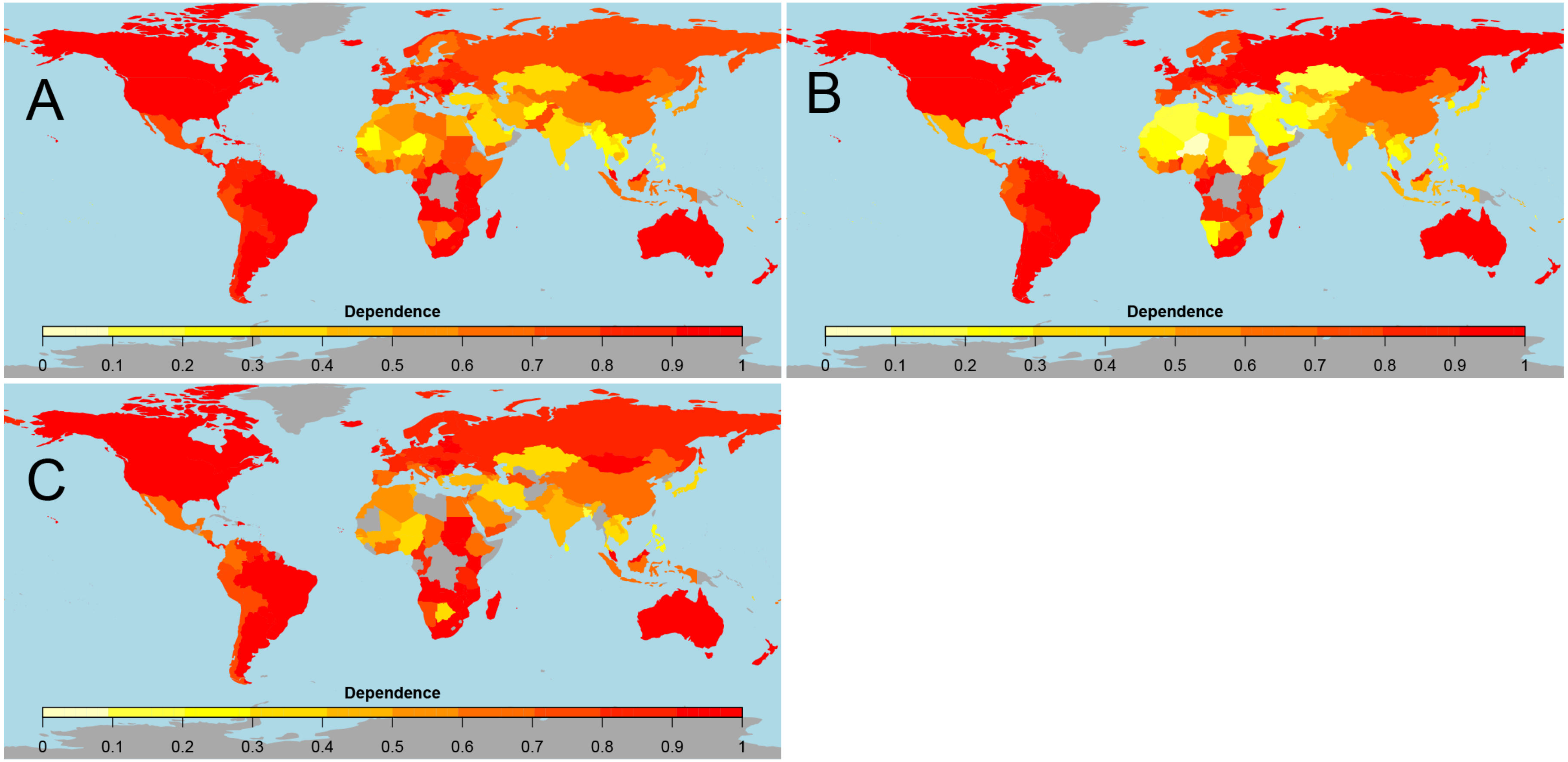

Figure 4. Degree of dependence per country on crops whose genetic diversity originates outside their borders in national production systems [(A) production quantity, (B) harvested area, and (C) production value] as a modeled mean between minimum and maximum dependence per country, 2009-2011. Dependence scale is degree of dependence (1 = completely dependent). As examples, (A) demonstrates that Australia (dark red) is highly dependent on ”foreign” crops measured in tonnes of food produced nationally (estimated value is 99.9% ± 1.10), and (B) shows that Egypt (orange) has a medium level of dependence measured in hectares of production nationally (estimated value is 52.2% ± 1.2).

Countries' dependence on "foreign" crops has increased over time

23. National dependence upon crops of "foreign" primary regions of diversity increased significantly as a global mean for all food supplies and production systems variables over the past half century (Figure 5, Supplementary Tables 3-4). Dependence in regard to calories increased from 62.7% to 67.4%, protein from 63.1% to 68.1%, fat from 63.4% to 73.2%, and food weight from 65.2% to 69.7% as measured in change in dependence from the mean of the first three years (1961-1963) to the last three years (2007-2009) per country, averaged across countries worldwide. Likewise, dependence in regard to production quantity increased from 63.9% to 68.6%, harvested area from 59.0% to 62.1%, and production value from 64.6% to 70.7% between 1961 and 2011.

24. Countries with the greatest increases in dependence over the period were located in Africa, West, South, Southeast, and East Asia, Central America, and Andean and tropical South America (Supplementary Figure 6). A number of countries with the largest changes in dependence upon crops of "foreign" primary regions of diversity in contribution to their food supplies were also those with major transitions in their production systems during the past 50 years (e.g., the growth of oil palm cultivation in Malaysia and Indonesia, a crop whose primary regions of diversity are located in West and Central Africa and the Neotropics; and soybean in Brazil, a crop of East Asian origin). Most regions also contained countries with decreases in dependence over the period. Growing consumption of major staples within the native regions of these crops, such as soybean in China, or wheat in West Asia, may be a factor in this decrease. Dependence in regard to fat in food supplies increased the greatest degree over the past 50 years among all variables, a trend that is concordant with significant changes in the contributing crop species composition of national food supplies globally over this period[2].

Countries' dependence on "foreign" crops is associated with diverse food supplies and production systems, and GDP

Dependence upon crops of "foreign" primary regions of genetic diversity was positively correlated with diverse food supplies and production systems, although high dependence also occurred in numerous countries exhibiting low diversity (Figure 6). Very few countries, on the other hand, showed high diversity in their food supplies and/or production systems and at the same time low dependence on "foreign" crops. Dependence was also associated with national Gross Domestic Product, although with considerable variation worldwide (Figure 7).

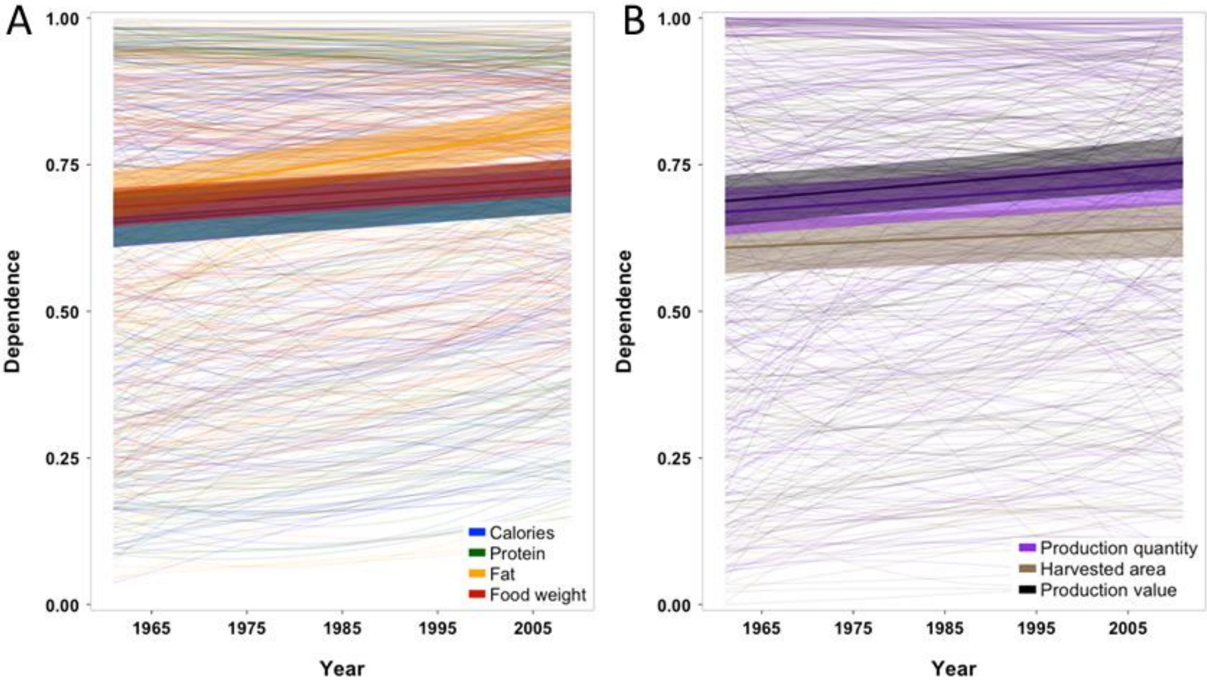

Figure 5. Increasing dependence on "foreign" crops in (A) national food supplies from 1961 to 2009 and (B) production systems from 1961 to 2011. Lines represent change over time in the mean between minimum and maximum dependence for each country in each year for each variable as predicted by a quadratic regression. Transparent ribbons represent modeled mean change across all countries (± 95% credible interval) in dependence for each variable, estimated using a Bayesian model with an interval censored response variable bounded between minimum and maximum dependence. See Supplementary Figure 6 for world maps displaying slopes of change in dependence per country for all measured food supply and production variables.

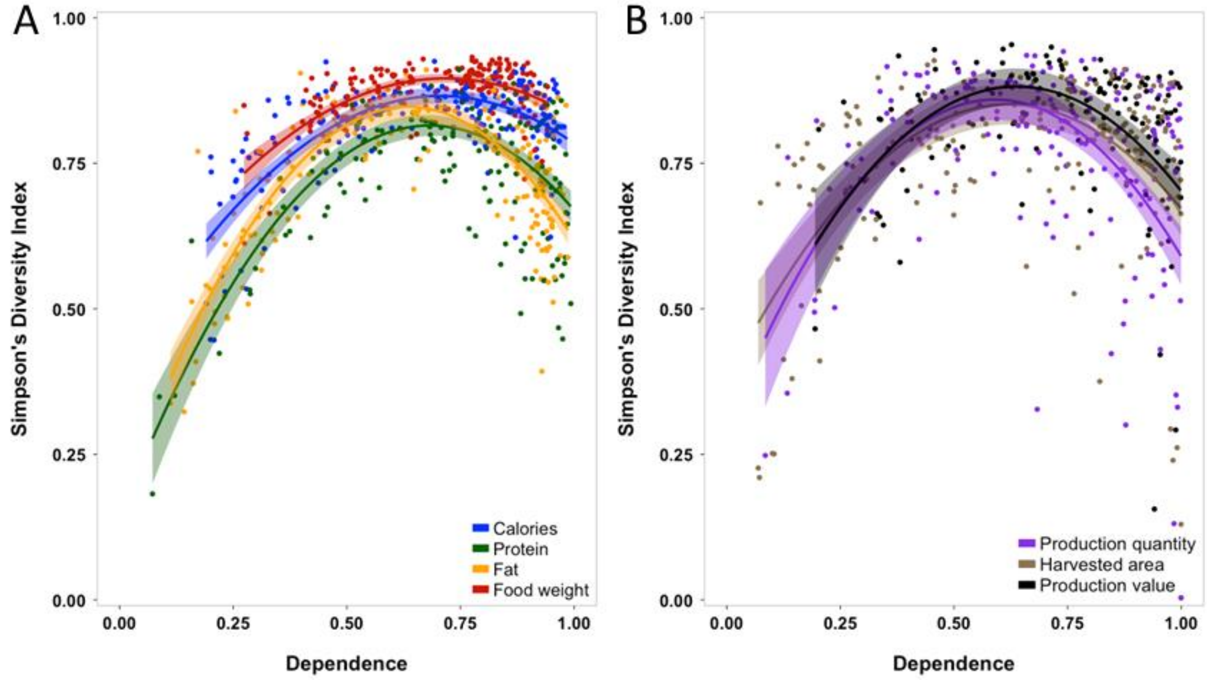

Figure 6. Positive correlation globally between national (A) food supply or (B) production system diversity, and dependence on "foreign" crops, as a modeled mean between minimum and maximum dependence per country, 2009-2011. Each dot for each color represents the value for a country. Dependence scale is degree of dependence (1 = completely dependent). Simpson's Index scale is degree of diversity in food supplies/production systems (1 = highly diverse). Shaded areas around each line represent the 95% confidence interval of the predicted relationship between mean diversity and mean dependence.

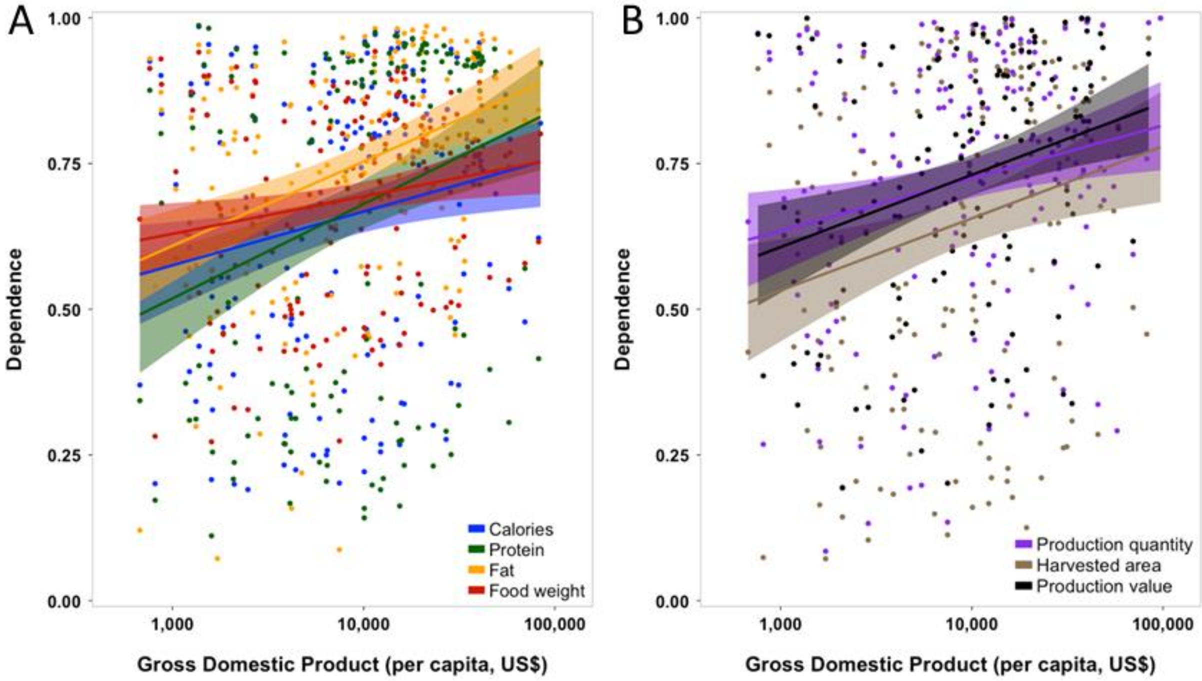

Figure 7. Positive correlation globally between per capita gross domestic product (GDP) and national (A) food supply or (B) production systems dependence on "foreign" crops, as a modeled mean between minimum and maximum dependence per country, 2009-2011. Each dot for each color represents the value for a country. Dependence scale is degree of dependence (1 = completely dependent). Shaded areas around each line represent the 95% confidence interval of the predicted relationship between mean GDP and mean dependence.

Discussion

25. The global food system is comprised of crops that were initially domesticated and further developed over long periods in specific geographic regions. These areas are concentrated in the tropics and subtropics but also include temperate regions in both hemispheres. These regions are the historical geographic source of a rich diversity of genetic resources, including traditional crop landraces and related wild species. After decades of genetic erosion in the wake of economic development and globalization, what remains of this diversity, as well as the range of breeding materials derived from this diversity, represent a vitally important portion of the global food system's raw material for further crop improvement and its genetic safety net against hunger. Conserving remnant crop and wild relative diversity *in situ*, collecting for storage in genebanks *ex situ*, ensuring that germplasm repositories are equipped to safeguard and distribute these plant genetic resources over the long term, generating useful data regarding the diversity present within these resources, and enabling access to this diversity constitute critically important steps in maximizing the potential contribution of plant genetic resources to global food security.[4,6-7,22,30]

26. The food supplies and production systems of countries worldwide are highly dependent on crops whose genetic diversity originates largely from beyond their borders. While geography and climate restricted the availability of these plants to their regions of origin for some period following the agricultural revolutions ca. 10,000 BP, growth in human migration, colonialism, and trade, among other historical forces,[47] increased the reach of crops beyond their primary regions, and ongoing economic and agricultural development and

globalization are making important food crops comprehensively available worldwide.[2] Even countries located within the most ancient and richest primary regions of diversity, e.g., West Asia, now exhibit considerable dependence on crops of "foreign" primary regions of diversity in their food supplies and production systems. As countries increase their GDP and diversify their diets in order to enhance economic, food, and nutrition security, dependence on "foreign" crops in their food systems is likely to further increase. Moreover, greater emphasis on nutritional quality as well as resilience in the face of climate change and natural resource limitations will heighten the need for diverse genetic materials in crop breeding,[32,48-50] further enhancing global interdependence in plant genetic resources.

Particularly in the case of the more globally important food crops, the pedigrees of varieties are complex, including materials developed from many distinct parts of the world. Seventeen major genetic parents of modern bread wheat, for instance, source from breeding lines developed in Europe, India, Korea, Japan, Africa, the United States, Uruguay, and Australia, along with the Russian Federation, Turkey, and Palestine.[1,39] Many generations of farmers as well as the significant work of plant breeders in diverse regions worldwide contributed to the provision of genetic resources for the development of such improved varieties.

27. The importance of continued access to diverse plant genetic resources through international exchange in support of national production, and its corollary impact on national economies, is unequivocal. Yet access to genetic diversity of important crops by major producers, wherever their location, is equally critical for the reliable provisioning of global food supplies via international trade, especially as countries have transitioned from food insecurity to trade dependence.[51-54] Production of the major crops is unevenly distributed across countries and for many crops now generally occurs outside of the primary regions of diversity of those crops, e.g., China, India, the USA, the Russian Federation, France and Canada for wheat; the USA, China, Germany, France, Brazil, and Argentina for maize; the USA, Brazil, Argentina and India for soybean; and China, India, the Russian Federation, Ukraine, and the USA for potatoes.[25]

28. The evidently very high levels of interdependence among countries in plant genetic resources bolsters the rationale considering this diversity as a public good, which should be proactively conserved and made available as freely as possible worldwide. Internationally coordinated mechanisms to facilitate access to these resources, most pertinently the MLS created within the Plant Treaty, are therefore needed. This interdependence also reinforces the importance of the genebank collections safeguarded for the global community by the CGIAR international agricultural research centres, which are covered under Article 15 of the Plant Treaty. While the long-term sustainability of funding for these collections has partially been achieved,[55] an increased level of support will be required to secure their role in conserving and distributing the genetic resources of their mandate crops. Moreover, large gaps remain in the conservation of crop diversity not covered by CGIAR collections.[30,56] The window of opportunity for securing the world's agricultural diversity threatened *in situ* and in under-funded genebanks will not remain open indefinitely.[7,27,30]

29. A comprehensive MLS should engender facilitated access to the genetic resources of all crops of present and future international importance. The MLS has thus far focused on cereal, pulse, starchy root, and forage crops (listed in Annex 1 of the Plant Treaty), thus oil crops, vegetables and fruits are not well covered. We estimate that as much as 28.7% of calories in global aggregate food supplies, 19.0% of protein, 61.0% of fat, 43.4% of food weight; and 41.0% of total global production quantity, 27.0% of harvested area, and 41.2% of global production value are comprised of crops not currently covered by the MLS (see Supplementary Table 5 for data on specific crops). As food systems continue to evolve due both to dietary change[2,11] and to novel production challenges,[9-10,48] a broadly inclusive and adaptable effort to conserve and provide access to plant genetic resources globally is at the very least prudent.

Acknowledgements

Financial support came from the "Adapting agriculture to climate change: collecting, protecting and preparing crop wild relatives" project, which is supported by the Government of Norway, managed by the Global Crop Diversity Trust with the Millennium Seed Bank of the Royal Botanic Gardens, Kew, UK, and implemented in partnership with national and international genebanks and plant breeding institutes around the world. For further information, see www.cwrdiversity.org/.

References

1. Flores-Palacios X (1998) *Contribution to the Estimation of Countries' Interdependence in the Area of Plant Genetic Resources.* Commission on Genetic Resources for Food and Agriculture, Background Study Paper No. 7, Rev. 1 (Food and Agriculture Organization of the United Nations, Rome).
2. Khoury CK, Bjorkman AD, Dempewolf H, Ramírez-Villegas J, Guarino L, Jarvis A, *et al.* (2014) Increasing homogeneity in global food supplies and the implications for food security. *Proc. Natl. Acad. Sci.* 111:4001-4006.
3. Xiao J, Grandillo S, Ahn SN, McCouch SR, Tanksley SD (1996) Genes from wild rice improve yield. *Nature* 384:223-224.
4. Hoisington D, Khairallah M, Reeves T, Ribout J-M, Skovmand B, Taba S, Warburton M (1999) Plant genetic resources: what can they contribute toward increased crop productivity? *Proc. Natl. Acad. Sci.* 96:5937-5943.
5. Zhu Y, Chen H, Fan J, Wang Y, Li Y, Chen J, *et al*. (2000) Genetic diversity and disease control in rice. *Nature* 406:718-722.
6. Gepts P (2006) Plant genetic resources conservation and utilization: the accomplishments and future of a societal insurance policy. *Crop Sci.* 46:2278-2292.
7. Esquinas-Alcázar J (2005) Protecting crop genetic diversity for food security: political, ethical and technical challenges. *Nat. Rev. Genet.* 6(12):946-953.
8. Guarino L, Lobell DBA (2011) A walk on the wild side. *Nature Climate Change* 1:374-375.
9. Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008) Prioritizing climate change adaptation needs for food security in 2030. *Science* 319:607-610.
10. Cordell D, Drangert J-O, White S (2009) The story of phosphorus: global food security and food for thought. *Global Env. Change* 19:292-305.
11. Kearney J (2010) Food consumption trends and drivers. *Phil. Trans. Royal Soc. B: Biol. Sci*. 365:2793-2807.
12. Kastner T, Rivas MJI, Koch W, Nonhebel S (2012) Global changes in diets and the consequences for land requirements for food. *Proc. Natl. Acad. Sci.* 109:6868-6872.
13. Vavilov NI (1926) Tzentry proiskhozhdeniya kulturnykh rastenii (The centres of origin of cultivated plants). *Works of Applied Botany and Plant Breeding* 16, 248pp.
14. Vavilov NI (1951) The origin, variation, immunity and breeding of cultivated plants (Translated by K. Start). *Cron. Bot.* 13:1-366.
15. Vavilov NI (1992) *Origin and Geography of Cultivated Plants* (Translated by Doris Löve) (Cambridge University Press, Cambridge, UK).
16. Harlan JR (1951) Anatomy of Gene Centers. *American Naturalist* 8(821):97-103
17. Zhukovsky PM (1965) Main gene centres of cultivated plants and their wild relatives within the territory of the U.S.S.R. *Euphytica* 14:177-188.
18. Zhukovsky PM (1968) New centres of origin and new gene centres of cultivated plants including specifically endemic microcentres of species closely allied to cultivated species. *Bot. J.* (*Russian Bot Z.*) 53:430-460.
19. Harlan JR (1971) Agricultural origins: centres and noncentres, *Science* 174: 468-474.
20. Zeven AC, Zhukovsky P (1975) *Dictionary of Cultivated Plants and Their Centres of Diversity: Excluding Most Ornamentals, Forest Trees and Lower Plants* (CAPD, Wageningen, Netherlands).
21. Zeven AC, De Wet JMJ (1982) *Dictionary of Cultivated Plants and Their Regions of Diversity: Excluding Most Ornamentals, Forest Trees and Lower Plants* (CAPD, Wageningen, Netherlands).
22. Harlan JR (1975) *Crops and Man* (American Society of Agronomy and Crop Science Society of America, Madison).
23. Nuijten E, van Treuren R, Struik PC, Mokuwa A, Okry F, Teken B, Richards P (2009) Evidence for the emergence of new rice types of interspecific hybrid origin in West African farmers' fields. *PLoS One* 4:e7335.
24. Jarvis A, Ramirez-Villegas J, Herrera-Campo BV, Navarro-Racines C (2012) Is cassava the answer to African climate change adaptation? *Tropical Plant Biology* 5(1):9-29.

25. FAO (2015) FAOSTAT (Food and Agriculture Organization of the United Nations, Rome). Available at http://faostat3.fao.org/.

26. Zurita-Silva A, Fuentes F, Zamora P, Jacobsen S-E, Schwember AR (2014) Breeding quinoa (*Chenopodium quinoa* Willd.): potential and perspectives. *Mol. Breed*. 34(1):13-30.

27. Wilkes G (2007) Urgent notice to all maize researchers: disappearance and extinction of the last wild teosinte population is more than half completed. A modest proposal for teosinte evolution and conservation in situ: the Balsas, Guerrero, Mexico. *Maydica* 52:49-58.

28. van de Wouw M, Kik C, van Hintum T, van Treuren R, Visser B (2009) Genetic erosion in crops: concept, research results and challenges. *Plant Gen. Res.* 8:1-15.

29. van de Wouw M, van Hintum T, Kik C, van Treuren R, Visser B (2010) Genetic diversity trends in twentieth century crop cultivars: a meta-analysis. *Theor. Appl. Gen*. 120:1241-1252.

30. FAO (2010) *Second Report on the State of the World's Plant Genetic Resources for Food and Agriculture* (Food and Agriculture Organization of the United Nations, Rome, Italy).

31. Thormann I, Fiorino E, Halewood M, Engels JMM (2015) Plant genetic resources collections and associated information as a baseline resource for genetic diversity studies: an assessment of the IBPGR-supported collections. *Genet. Resour. Crop Evol.* doi 10.1007/s10722-015-0231-9.

32. McCouch S, Baute GJ, Bradeen J, Bramel P, Bretting PK, Buckler E, *et al.* (2013) Agriculture: feeding the future. *Nature* 499:23-24.

33. Fowler C, Hodgkin T (2004) Plant genetic resources for food and agriculture: assessing global availability. *Ann. Rev. Environ. Res.* 29:143-179.

34. Bjørnstad Å, Tekle S, Göransson M (2013) 'Facilitated access' to plant genetic resources: does it work? *Gen. Res. Crop Evol.* 60:1959-1965.

35. Kloppenburg JJr, Kleinman DL (1987) Analyzing empirically the distribution of the world's plant genetic resources: the plant germplasm controversy. *Bioscience* 37:190-198.

36. Dudnik NS, Thormann I, Hodgkin T (2001) The extent of use of plant genetic resources in research - a literature survey. *Crop Sci.* 41:6-10.

37. Smale M, Day Rubenstein K (2002) The demand for crop genetic resources: international use of the U.S. National Plant Germplasm System. *World Dev.* 30:1639-1655.

38. Day Rubenstein K, Smale M (2004) *International Exchange of Genetic Resources, The Role of Information and Implications for Ownership: The Case of the U.S. National Plant Germplasm System*. EPTD Discussion Paper no. 119. (Environment and Production Technology Division, International Food Policy Research Institute (IFPRI), Washington DC).

39. Smale M (1996) *Understanding Global Trends in the Use of Wheat Diversity and International Flows of Wheat Genetic Resources*. Economics Working Paper, 96 (2). (International Maize and Wheat Improvement Center [CIMMYT]).

40. Gollin D (1998) Valuing farmers' rights. *Agricultural Values of Plant Genetic Resources*, In: eds Evenson RE, Gollin D, Santaniello V (CAB International, Wallingford, UK), pp. 233-245).

41. Brennan JP, Godden D, Smale M, Meng E (1999) Breeder demand for and utilization of wheat genetic resources in Australia. *Plant Varieties and Seeds* 12:113-127.

42. Zhou X, Carter TEJr, Cui Z, Miyazaki S, Burton JW (2000) Genetic base of Japanese soybean cultivars released during 1950 to 1988. *Crop Sci.* 40:1794-1802.

43. Cassaday K, Smale M, Fowler C, Heisey PW (2001) Benefits from giving and receiving genetic resources: the case of wheat. *Plant Gen. Res. News.* 127:1-10.

44. Fowler C, Smale M, Gaiji S (2001) Unequal exchange? Recent transfers of agricultural resources and their implications for developing countries. *Devel. Pol. Rev.* 19:181-204.

45. Smale M, Reynolds MP, Warburton M, Skovmand B, Trethowan RM, Singh RP, *et al.* (2002) Dimensions of diversity in modern spring bread wheat in developing countries from 1965. *Crop Sci.* 42:1766-1779.

46. Johnson NL, Pachico D, Voysest O (2003) The distribution of benefits from public international germplasm banks: the case of beans in Latin America. *Agric. Econ.* 29:277-286.

47. Diamond J (2004) The wealth of nations. *Nature* 429:616-617.

48. Jarvis A, Ramirez-Villegas J, Hanson J, Leibing C (2009) Crop and forage genetic resources: international interdependence in the face of climate change. *The Impact of Climate Change on Countries' Interdependence on Genetic Resources for Food and Agriculture.* Background Study Paper No.48, eds Fujisaka S, Williams D, Halewood M (FAO Commission on Genetic Resources for Food and Agriculture, FAO, Rome).

49. Burke MB, Lobell DB, Guarino L (2009) Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. *Global Environ. Change* 19:317-325.

50. Khoury CK, Jarvis A (2014) *The Changing Composition of the Global Diet: Implications for CGIAR Research*. CIAT Policy Brief No. 18. (Centro Internacional de Agricultura Tropical, Cali, Colombia, 6 pp.).

51. Fader M, Gerten D, Krause M, Lucht W, Cramer W (2013) Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. *Env. Res. Lett.* 8:014046.

52. Porkka M, Kummu M, Siebert S, Varis O (2013) From food insufficiency towards trade dependency: a historical analysis of global food availability. *PLoS One* 8:e82714.

53. D'Odorico P, Carr JA, Laio F, Ridolfi L, Vandoni S (2014). Feeding humanity through global food trade. *Earth's Future* 2:458-469.

54. MacDonald GK, Brauman KA, Sun S, Carlson KM, Cassidy, ES, Gerber JS, West PC (2015) Rethinking agricultural trade relationships in an era of globalization. *BioScience* 65:275-289.

55. Global Crop Diversity Trust (2013) *Fundraising Strategy 2014-2018* (Global Crop Diversity Trust, Bonn, Germany).

56. Khoury C, Laliberté B, Guarino L (2010) Trends in *ex situ* conservation of plant genetic resources: a review of global crop and regional conservation strategies. *Gen. Res. Crop Evol.,* 57:625-639.

57. Engels J, Hodgkin T, Thormann I, Robinson J, Fowler C (2001) *Crops Proposed for the Multilateral System: Centres of Diversity, Locations of Ex Situ Collections, and Major Producing Countries.* Background Study Paper No. 12 (CGRFA/CG-4/00/Inf.4) of the Fourth Inter-Sessional Meeting of the Contact Group of the CGRFA Secretariat (Food and Agriculture Organization of the United Nations, Rome).

58. Vincent H, Wiersema J, Kell S, Fielder H, Dobbie S, Castañeda-Álvarez NP, *et al.* (2013) A prioritized crop wild relative inventory to help underpin global food security. *Biol. Conserv.* 167:265-275.

59. GRIN (Germplasm Resources Information Network) (2014) USDA, ARS, National Genetic Resources Program, Beltsville. (accessed on 1 July 2014). Available at http://www.ars-grin.gov/cgi-bin/npgs/html/tax_search.pl.

60. Prota (Plant Resources of Tropical Africa) (2014) Prota4u online database. (accessed on 1 July 2014). Available at http://www.prota4u.info/.

61. Abel GJ, Sander N (2014) Quantifying Global International Migration Flows. *Science* 343:1520-1522.

62. Gelman A, Hill J (2007) *Data Analysis using Regression and Multilevel/Hierarchical Models* (Cambridge University Press, New York).

63. Gelman A, Rubin DB (1992) Inference from iterative simulation using multiple sequences. *Statistical Science* 7:457-472.

64. World Bank (2014) International Comparison Program database. (accessed on 19 September 2014). Available at http://data.worldbank.org/.

65. Prescott-Allen R, Prescott-Allen C (1990) How many plants feed the world? *Cons. Bio.* 4:365-374.

66. Doughty J (1979) Dangers of reducing the range of food choice in developing countries. *Ecology of Food and Nutrition* 8:275-283.

Annex I: Methods and Materials

Food supplies and production data

We analyzed the full set of food crop commodities included in food supplies and production data provided by FAO[25] [for food supplies: calories (kcal/capita/day), protein (g/capita/day), fat (g/capita/day), and food weight (g/capita/day); for production systems: production quantity (tonnes), harvested area (ha), and gross production value (million US$)]. National 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 non-food products, and losses during storage and transport.[2] While food supplies data accounts only for direct human consumption, production data for crops such as maize and soybean is potentially inclusive of livestock and industrial uses as well as human food. In the production analysis we also included agricultural crops indirectly contributing to human food supplies via livestock production (i.e., alfalfa, clover, and vetch). Non-food (e.g., industrial and fibre) crops as well as animal product commodities were not included in the analysis. Plant commodities comprised of the same crop species were aggregated into single commodities representing the crop, e.g., sesame seed oil and sesame seed. After aggregation, 53 crop commodities remained in food supplies data, and 132 crop commodities in production data (Supplementary Table 6). See Table S1 of Khoury *et al.* (2014)[2] for a comprehensive listing of the crop species included in the commodities treated in food supplies data.

For current food supplies and production systems, we analyzed data for each crop commodity per country per measurement over the most recent three years for which sufficient data were available (2009-2011). All (177) countries consistently reported during the time period were included for food supplies variables, as well as for production quantity and harvested area (Supplementary Table 7), covering 98.5% of the world's population. All (141) countries reported for (current million US$) production value were included, covering 94.1% of the world's population.[25]

For the analysis of change in dependence over time, food supplies data were assessed for each year from 1961-2009, and production systems from 1961-2011, utilizing the full set of commodity and country listings, standardized across all years. In order to align all time periods and include as much of the world's population as possible, the current countries formerly comprising the USSR, Yugoslav SFR, Ethiopia PDR, and Czechoslovakia were aggregated into their former countries, with national data summed per year for production measurements, and merged by weighted average based upon the population of the respective states during the respective reporting year for per capita food supplies measurements. Belgium and Luxembourg were reported together during 1961-1999 and therefore recent years listing the countries separately were merged as above. Countries that did not have estimates in every year between 1961 and 2009/2011 were removed from the analysis. The resulting 152 comparable countries treated in food supplies data comprised 98% of the world's population across the study period.[2] The 182 comparable countries covered in production quantity and harvested area data comprised 99.7% of the global population, and the 115 countries covered in (constant 2004-2006 million US$) production value data covered 88.5% (Supplementary Table 7).

Primary regions of diversity of crops

Primary regions of diversity were assigned based upon primary and secondary literature regarding centres of crop diversity, origins of crop domestication, and high species richness of closely related wild plants.[1,16-21,57-60] Regional classifications followed those listed in Annex 2 of the FAO State of the World's Plant Genetic Resources for Food and Agriculture,[30] modified to more accurately represent eco-geographic parameters driving plant species distributions. Specifically, both western and eastern Europe were split into north and south regions to account for temperate versus Mediterranean ecologies; Australia and New Zealand were segregated from remaining (tropical) islands of the Pacific region; and South America was split into Andean, temperate, and tropical regions. A total of 23 eco-geographic regions were delineated (Supplementary Figure 7). Countries whose boundaries included more than one eco-geographic region were included in all appropriate regions in order to be as inclusive as possible and thus avoid overestimations of dependence (e.g., Colombia was assigned both to Andean and to tropical South American regions) (Supplementary Table 7).

Crops whose primary areas of diversity encompassed more than one eco-geographic region were listed in all appropriate regions (e.g., wheat was listed in Central Asia, West Asia, and the South and East Mediterranean). Forty-two of the 53 crop commodities treated in food supplies data, and 116 of the 132 crops in production data, were assignable to primary regions of diversity, with the remaining general commodities which were not clearly attributable to specific crop species listed as "not specified" (Supplementary Table 6).

We constructed circular plots displaying the relative importance of primary regions of diversity as sources of crops comprising current (2009-2011 average) national food supplies and production systems, using methods and code adapted from Abel and Sander (2014).[61] For recipient data, regional food supply values (kcal or g, /capita/day) were formed per variable by deriving a weighted average across countries comprising each region, with national values weighted by population. Regional production values were calculated by summing values across countries comprising each region for each variable.

Dependence on "foreign" primary regions of diversity

We estimated the degree to which a country's food supplies and production systems are dependent upon crops of "foreign" primary regions of diversity by determining the extent to which such supplies/systems are composed of crops whose primary regions of diversity do not coincide with the regions within which that country is located (see Supplementary Table 8 as an example for Colombia). The method was initiated with the assumption that crops within a given country's food supplies/production systems were completely "foreign" (100% dependence). The percent contribution of all crops whose primary regions of diversity were identified as in the same region as the country was then subtracted to estimate a "maximum dependence" metric per country (Equation 1) [modified from Flores-Palacios (1998)].[1] In this metric, those general crop commodities whose regions could not be specified were assumed to be of "foreign" primary regions of crop diversity.

Supplementary Table 8. Food supply of Colombia as measured in calories (kcal/capita/day) (2009-2011 average), with primary regions of diversity of contributing crops.

COMMODITY	CALORIES (KCAL/ CAPITA/ DAY)	% OF TOTAL	PRIMARY REGIONS OF DIVERSITY	ASSIGNMENT
SUGAR	347.7	16.7%	South Asia, Southeast Asia, Europe, South and East Mediterranean	Foreign
RICE	296.7	14.3%	East Asia, South Asia, Southeast Asia, Central Africa, West Africa	Foreign
MAIZE	258.7	12.5%	Central America and Mexico	Foreign
WHEAT	235.0	11.3%	Central Asia, West Asia, South and East Mediterranean	Foreign
PALM OIL	228.0	11.0%	Central Africa, West Africa, Central America and Mexico, Tropical South America	Native
SOYBEAN	136.3	6.6%	East Asia	Foreign
BANANAS & PLANTAINS	127.7	6.1%	South Asia, Southeast Asia	Foreign
CASSAVA	91.0	4.4%	Tropical South America, Central America and Mexico	Native
POTATOES	60.7	2.9%	Andean South America	Native
BARLEY	48.3	2.3%	Central Asia, West Asia, South and East Mediterranean	Foreign
FRUITS, OTHER	32.0	1.5%	Not specified	Not specified
BEANS	30.3	1.5%	Central America and Mexico, Andean South America	Native
BEVERAGES, ALCOHOLIC	19.0	0.9%	Not specified	Not specified
YAMS	17.3	0.8%	West Africa, South Asia, Southeast Asia	Foreign
PEAS	16.0	0.8%	East Africa, West Asia, Southern Europe, South and East Mediterranean	Foreign
PULSES, OTHER	16.0	0.8%	Africa, South Asia, West Asia, South and East Mediterranean	Foreign
VEGETABLES, OTHER	13.3	0.6%	Not specified	Not specified
SUNFLOWER	12.0	0.6%	North America	Foreign
CITRUS, OTHER	11.3	0.5%	Not specified	Not specified
ONIONS	10.3	0.5%	Central Asia, West Asia	Foreign
COCONUTS	7.7	0.4%	South Asia, Southeast Asia, Tropical Pacific region	Foreign
TOMATOES	7.3	0.4%	Andean South America	Native
ORANGES & MANDARINS	6.0	0.3%	East Asia	Foreign
PINEAPPLES	6.0	0.3%	Tropical South America	Native
RAPE & MUSTARD	5.3	0.3%	Southern Europe, South and East Mediterranean	Foreign
COCOA BEANS	5.0	0.2%	Central America and Mexico, Tropical South America	Native
COTTONSEED OIL	4.3	0.2%	East Africa, Southern Africa, Caribbean, Central America and Mexico, Tropical South America	Native
GROUNDNUT	4.0	0.2%	Tropical South America	Native
SPICES, OTHER	4.0	0.2%	Not specified	Not specified
GRAPES	3.3	0.2%	North America, East Asia, West Asia, South and East Mediterranean	Foreign
ROOTS, OTHER	3.0	0.1%	Caribbean, Central America and Mexico, Tropical South America, South Asia, Southeast Asia, Tropical Pacific region	Native
APPLES	2.7	0.1%	Central Asia, East Asia, Europe	Foreign
SWEETENERS, OTHER	2.0	0.1%	Not specified	Not specified
COFFEE	1.3	0.1%	Central Africa, East Africa, West Africa	Foreign
MISCELLANEOUS	1.3	0.1%	Not specified	Not specified
OLIVES	1.3	0.1%	East Africa, West Asia, Southern Europe, South and East Mediterranean	Foreign
LEMONS & LIMES	1	0.0%	East Asia, South Asia	Foreign
OATS	1	0.0%	Northern Europe	Foreign
SESAME	1	0.0%	East Africa, South Asia, West Asia	Foreign
TREENUTS	1	0.0%	Not specified	Not specified

Equation 1: Metric of maximum dependence = 100% - Σ% crops for which the country forms part of a primary region of diversity

The sum of the percent contribution of these non-specified general crop commodities was then subtracted, resulting in a "minimum dependence" metric which assumes that all non-specified crop commodities possess primary regions of diversity within the same region as the country (Equation 2).

Equation 2: Metric of minimum dependence = 100% - Σ% crops for which the country forms part of a primary region of diversity - Σ% crop commodities not specified to regions

Mean dependence in food supplies and production systems per country was estimated using an interval censoring method, where the response variable (the calculated dependence value in each country in each year) was bounded between the minimum and maximum dependence estimates for each observation. A model of this type allows the uncertainty around an observation to be incorporated into the parameter estimates for the parameter of interest. For estimates of current dependence, we modelled the mean of the most recent three years (2009-2011). For estimates of change in dependence from 1961-2009/2011, intercepts and slopes per country were modelled as random effects, where the mean hyper-parameter for the random slopes represented the estimated slope (change in dependence over time) across all countries. We allowed a correlation between country-level intercepts and slopes to account for the fact that countries with high dependence have weaker dependence-time relationships than countries with low dependence.[62] The interval-censored models were implemented using a Bayesian framework in JAGS (v. 3.4.0) called from R (v.3.1.1), using the packages rjags and R2jags. Non-informative ("flat") priors were used for all coefficients. Convergence was assessed using the Gelman-Rubin diagnostic[63] and by visual inspection of trace plots. Dependency values reported in the text represent the model-estimated coefficient, ± the standard deviation. Credible intervals for each parameter are reported in Supplementary Tables 2-4.

We used Simpson's diversity index to correlate the degree of contributing crop diversity in current (2009-2011 mean) national food supplies/production systems with dependence on crops of "foreign" primary regions of diversity under the same time period. The diversity-dependence relationship was modelled using a simple linear model with both linear and quadratic terms, using the vegan package in R (v. 3.1.1). We also correlated dependence with national Gross Domestic Product (GDP) per capita purchasing power parity, using a mean GDP value across 2009-2011 for 169 available countries.[64]

Importance of food crops

Crops were assigned importance individually for each food supplies and production systems variable into 10% quantiles, from 1 (low importance) to 10 (high importance), based upon their global aggregate (food supplies) and total global production values. A combined assessment was performed on (136) unique crop commodities covered in food supplies and production systems data (Supplementary Table 5). Thirty-seven of these commodities possessed both food supplies and production systems data and were directly compared. An additional 92 crop commodities with production systems values were embedded within 12 general commodities in food supplies data (i.e., cereals, other; fruits, other; oilcrops, other; oranges & mandarins; pulses, other; rape & mustard; roots, other; spices, other; sugar; tea; treenuts; and vegetables, other). Food supplies values for most of the individual commodities were estimated by dividing their total general commodity values equally across listed crops. For the sugar commodity, sugarcane was assigned 70% and sugar beet 30% of the total value; for the tea commodity, tea [*Camellia sinensis* (L.) Kuntze] was assigned 80%, mate 10%, and "not elsewhere specified" (nes) tea 10%. Three additional production systems crop commodities (alfalfa, clover, and vetches), which are livestock feed/forage crops and therefore are not recorded in food supplies data, were assessed through quantile values derived solely from production systems variables. Four general food supplies commodities (beverages, alcoholic; beverages, fermented; miscellaneous; and sweeteners, other) were not recorded in production systems variables, thus these commodities were assessed through quantile values derived solely from food supplies variables. Coverage of each crop in the MLS, i.e., Annex 1 of the Plant Treaty was assessed, listing crops as covered, partially covered (often in the case of general crop commodities, in which some portion of the crops within the commodity are covered in the MLS and others not), or not covered. The extent of geographic importance of crops was additionally documented by counting the number of countries listing each commodity (>0) for each variable, as well as listing the plant commodities by decreasing importance until the total contribution equaled 90% of each country's food supply/ production for each variable, a threshold which is inclusive of major contributors to supply/ production systems and exclusive of commodities contributing very small quantities.[2,65] The total count of countries including each crop commodity as important was then derived per crop commodity (Supplementary Table 5).

Data limitations and uncertainties

In this analysis we included all pertinent available variables for both food supplies and production systems that permit a globally comparable evaluation across countries. This said, a number of constraints to the data exist. First, food supply data is not directly equivalent to consumption, as food losses at the household level are not measured. The aggregation of numerous crops into several general commodities particularly in food supplies data, constrains the ability to assign all crop commodities to primary regions of diversity and thus to derive more specific dependence estimates without substantial degrees of uncertainty (i.e., between minimum and maximum dependence). In addition, such aggregation causes uncertainty within a number of crop commodities that are associated to regions, e.g., sugar in food supplies data, which may contain both sugarcane and sugar beet. Although both these crops may be associated to primary regions of diversity, the accurate assignment of dependence of any particular country's food supply in regard to the contribution of sugar is limited by the inability to disaggregate the specific contribution of each of these crops within the commodity. The assignment of crops and countries to regions also results in a degree of generalization due to the lack of accounting for natural variation within such regions. Iceland, for instance, was counted within north Western Europe, but the crops of primary diversity within this region are largely not indigenous to that island nation.

The range of crops covered in this analysis is not fully inclusive of all foodstuffs produced and consumed in national food systems, and thus an underestimation and/or overgeneralization of diversity is assumed, particularly in regard to plants primarily encountered in home gardens and local markets, seasonally important foods, and culinary herbs, spices and other crops consumed in relatively small quantities.[2,65] Although accounting for food weight, which may indirectly elucidate the importance of crops for essential nutrients other than calories, protein, and fat, food supply data does not specifically report statistics in regard to micronutrients, where a larger number crops contributing relatively small quantities individually may be of particular importance.[66]

In sum, the aggregation of some crop commodities, the generality of the defined eco-geographic regions, uncertainty for some crops as to their primary regions of diversity, and the subjective nature of the boundaries of such regions, lead to a degree of uncertainty in dependence metrics. Acknowledging these limitations, the results are a very strong indication of the extent of globalization of food systems and the resulting interdependence among nations on plant genetic resources. We also note that production data, which included a much more comprehensive list of crop commodities than food supplies data, resulted in equivalently high dependence values globally.