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Climate Change Impacts on Global Food Security

Tim Wheeler and Joachim von Braun

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34. J. Balanyá, J. M. Oller, R. B. Huey, G. W. Gilchrist, L. Serra, *Science* **313**, 1773–1775 (2006).
35. A. A. Hoffmann, C. M. Sgrò, *Nature* **470**, 479–485 (2011).
36. S. Lavergne, N. Mouquet, W. Thuiller, O. Ronce, *Annu. Rev. Ecol. Evol. Syst.* **41**, 321–350 (2010).
37. M. Kearney, R. Shine, W. P. Porter, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 3835–3840 (2009).
38. B. Sinervo *et al.*, *Science* **328**, 894–899 (2010).
39. J. Elith, M. Kearney, S. Phillips, *Methods in Ecology and Evolution* **1**, 330–342 (2010).
40. S. Ferrier, G. Manion, J. Elith, K. Richardson, *Divers. Distrib.* **13**, 252–264 (2007).
41. J. A. Wiens, D. Stralberg, D. Jongsomjit, C. A. Howell, M. A. Snyder, *Proc. Natl. Acad. Sci. U.S.A.* **106** (suppl. 2), 19729–19736 (2009).
42. J. Lenoir *et al.*, *Glob. Change Biol.* **19**, 1470–1481 (2013).
43. S. E. Williams, E. E. Bolitho, S. Fox, *Proc. R. Soc. London Ser. B Biol. Sci.* **270**, 1887–1892 (2003).
44. F. A. La Sorte, W. Jetz, *J. Anim. Ecol.* **81**, 914–925 (2012).
45. S. Dullinger *et al.*, *Nat. Clim. Change* **2**, 619–622 (2012).
46. J. A. Pounds, M. P. L. Fogden, J. H. Campbell, *Nature* **398**, 611–615 (1999).
47. C. A. Deutsch *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **105**, 6668–6672 (2008).
48. R. K. Colwell, G. Brehm, C. L. Cardelús, A. C. Gilman, J. T. Longino, *Science* **322**, 258–261 (2008).
49. M. Bálint *et al.*, *Nat. Clim. Change* **1**, 313–318 (2011).
50. I. G. Alsos *et al.*, *Proc. Biol. Sci.* **279**, 2042–2051 (2012).
51. W. H. Van der Putten, M. Macel, M. E. Visser, *Philos. Trans. R. Soc. London Ser. B Biol. Sci.* **365**, 2025–2034 (2010).
52. P. L. Zarnetske, D. K. Skelly, M. C. Urban, *Science* **336**, 1516–1518 (2012).
53. D. A. Keith *et al.*, *Biol. Lett.* **4**, 560–563 (2008).
54. T. E. Reed, V. Grøtan, S. Jenouvrier, B.-E. Sæther, M. E. Visser, *Science* **340**, 488–491 (2013).
55. R. A. Cooper *et al.*, *Geology* **34**, 241–244 (2006).
56. M. Foote, J. J. Sepkoski Jr., *Nature* **398**, 415–417 (1999).
57. R. Coope, *ESS Bull.* **2**, 57 (2004).
58. J. L. Blois, J. L. McGuire, E. A. Hadly, *Nature* **465**, 771–774 (2010).
59. P. L. Koch, A. D. Barnosky, *Annu. Rev. Ecol. Evol. Syst.* **37**, 215–250 (2006).
60. D. Nogués-Bravo, R. Ohlemüller, P. Batra, M. B. Araújo, *Evolution* **64**, 2442–2449 (2010).
61. C. H. Graham, C. Moritz, S. E. Williams, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 632–636 (2006).
62. S. T. Jackson, J. T. Overpeck, *Paleobiology* **26**, 194–220 (2000).
63. J. W. Williams, B. N. Shuman, T. Webb III, P. J. Bartlein, P. L. Leduc, *Ecol. Monogr.* **74**, 309–334 (2004).
64. D. K. Grayson, *Quat. Sci. Rev.* **25**, 2964–2991 (2006).
65. R. C. Terry, C. Li, E. A. Hadly, *Glob. Change Biol.* **17**, 3019–3034 (2011).
66. G. M. MacDonald *et al.*, *Prog. Phys. Geogr.* **32**, 139–172 (2008).
67. L. L. Knowles, B. C. Carstens, M. L. Keat, *Curr. Biol.* **17**, 940–946 (2007).
68. G. Hewitt, *Nature* **405**, 907–913 (2000).
69. A. C. Carnaval, M. J. Hickerson, C. F. B. Haddad, M. T. Rodrigues, C. Moritz, *Science* **323**, 785–789 (2009).
70. J. Provan, K. D. Bennett, *Trends Ecol. Evol.* **23**, 564–571 (2008).
71. A. Moussalli, C. Moritz, S. E. Williams, A. C. Carnaval, *Mol. Ecol.* **18**, 483–499 (2009).
72. R. C. Bell *et al.*, *Mol. Ecol.* **19**, 2531–2544 (2010).
73. A. U. Oza, K. E. Lovett, S. E. Williams, C. Moritz, *Mol. Phylogenet. Evol.* **62**, 407–413 (2012).
74. M. Byrne, *Quat. Sci. Rev.* **27**, 2576–2585 (2008).
75. R. Cheddadi *et al.*, *Glob. Ecol. Biogeogr.* **15**, 271–282 (2006).
76. C. Moritz *et al.*, *Philos. Trans. R. Soc. London Ser. B Biol. Sci.* **367**, 1680–1687 (2012).
77. A. Hampe, A. S. Jump, *Annu. Rev. Ecol. Evol. Syst.* **42**, 313–333 (2011).
78. U. M. A. Ramakrishnan, E. A. Hadly, *Mol. Ecol.* **18**, 1310–1330 (2009).
79. E. D. Lorenzen *et al.*, *Nature* **479**, 359–364 (2011).
80. I. C. Chen, J. K. Hill, R. Ohlemüller, D. B. Roy, C. D. Thomas, *Science* **333**, 1024–1026 (2011).
81. T. L. Root *et al.*, *Nature* **421**, 57–60 (2003).
82. C. J. B. Sorte, S. L. Williams, J. T. Carlton, *Glob. Ecol. Biogeogr.* **19**, 303–316 (2010).
83. W. W. L. Cheung *et al.*, *Nat. Clim. Change* **3**, 254–258 (2013).
84. S. Lavergne, J. Molina, M. A. X. Debussche, *Glob. Change Biol.* **12**, 1466–1478 (2006).
85. R. Menéndez *et al.*, *Proc. Biol. Sci.* **273**, 1465–1470 (2006).
86. R. J. Wilson, D. Gutiérrez, J. Gutiérrez, V. J. Monserrat, *Glob. Change Biol.* **13**, 1873–1887 (2007).
87. M. Lurgi, B. C. López, J. M. Montoya, *Philos. Trans. R. Soc. London Ser. B Biol. Sci.* **367**, 2913–2922 (2012).
88. M. T. Burrows *et al.*, *Science* **334**, 652–655 (2011).
89. S. M. Crimmins, S. Z. Dobrowski, J. A. Greenberg, J. T. Abatzoglou, A. R. Mynsberge, *Science* **331**, 324–327 (2011).
90. M. W. Tingley, M. S. Koo, C. Moritz, A. C. Rush, S. R. Beissinger, *Glob. Change Biol.* **18**, 3279–3290 (2012).
91. C. Moritz *et al.*, *Science* **322**, 261–264 (2008).
92. J. Lenoir *et al.*, *Ecography* **33**, 295–303 (2010).
93. A. L. Angert *et al.*, *Ecol. Lett.* **14**, 677–689 (2011).
94. A. L. Perry, P. J. Low, J. R. Ellis, J. D. Reynolds, *Science* **308**, 1912–1915 (2005).
95. G.-R. Walther *et al.*, *Nature* **416**, 389–395 (2002).
96. W. E. Bradshaw, C. M. Holzapfel, *Mol. Ecol.* **17**, 157–166 (2008).
97. J. L. Gardner, A. Peters, M. R. Kearney, L. Joseph, R. Heinsohn, *Trends Ecol. Evol.* **26**, 285–291 (2011).
98. C. Teplitsky, J. A. Mills, J. S. Alho, J. W. Yarrall, J. Merilä, *Proc. Natl. Acad. Sci. U.S.A.* **105**, 13492–13496 (2008).
99. D. Réale, A. G. McAdam, S. Boutin, D. Berteaux, *Proc. R. Soc. London Ser. B Biol. Sci.* **270**, 591–596 (2003).
100. A. Ozgul *et al.*, *Science* **325**, 464–467 (2009).
101. L. M. Eastman, T. L. Morelli, K. C. Rowe, C. J. Conroy, C. Moritz, *Glob. Change Biol.* **18**, 1499–1508 (2012).
102. A. E. Cahill *et al.*, *Proc. R. Soc. London Ser. B Biol. Sci.* **280**, 20121890 (2013).
103. K. R. Lips, J. Diffendorfer, J. R. Mendelson III, M. W. Sears, *PLoS Biol.* **6**, e72 (2008).
104. J. R. Rohr, T. R. Raffel, *Proc. Natl. Acad. Sci. U.S.A.* **107**, 8269–8274 (2010).
105. A. D. Barnosky *et al.*, *Nature* **486**, 52–58 (2012).
106. C. I. Millar, N. L. Stephenson, S. L. Stephens, *Ecol. Appl.* **17**, 2145–2151 (2007).
107. E. Jansen *et al.*, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2007), chap. 6.
108. E. M. Rubidge *et al.*, *Nat. Clim. Change* **2**, 285–288 (2012).

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REVIEW

Climate Change Impacts on Global Food Security

Tim Wheeler[1,2]* and Joachim von Braun[3]

Climate change could potentially interrupt progress toward a world without hunger. A robust and coherent global pattern is discernible of the impacts of climate change on crop productivity that could have consequences for food availability. The stability of whole food systems may be at risk under climate change because of short-term variability in supply. However, the potential impact is less clear at regional scales, but it is likely that climate variability and change will exacerbate food insecurity in areas currently vulnerable to hunger and undernutrition. Likewise, it can be anticipated that food access and utilization will be affected indirectly via collateral effects on household and individual incomes, and food utilization could be impaired by loss of access to drinking water and damage to health. The evidence supports the need for considerable investment in adaptation and mitigation actions toward a "climate-smart food system" that is more resilient to climate change influences on food security.

Tackling hunger is one of the greatest challenges of our time (*1*). Hunger has multiple dimensions and causes, ranging from deficiencies in macro- and micro-nutrients, through short-term shocks on food access, to chronic shortages. Causes range from constraints on the supply of food of sufficient quantity and quality and lack of purchasing power to complex interactions of nutrition with sanitation and infectious diseases leading to poor health. Several of these causes have been addressed in recent decades, and substantial progress has been made in reducing the proportion of the world's undernourished population from an estimated 980 million in 1990–92 to about 850 million in 2010–12 (*2*). However, from other relevant indicators of nutrition, such as child underweight and stunting and health surveys, an estimated 2 billion people still suffer from micro-nutrient deficiencies today.

The long-term reduction in the prevalence of undernutrition worldwide has slowed since 2007, as a result of pressures on food prices, economic

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volatilities, extreme climatic events, and changes in diet, among other factors. Furthermore, additional pressures on the global food system are expected to build in the future. For example, demand for agricultural products is estimated to increase by about 50% by 2030 as the global population increases (*3*), which will require a shift toward sustainable intensification of food systems (*4*). The impacts of climate change will have many effects on the global food equation, both for supply and demand, and on food systems at local levels where small farm communities often depend on local and their own production (*5*). Thus, climate change could potentially slow down or reverse progress toward a world without hunger.

Here, we offer an overview of the evidence for how climate change could affect global food security, with particular emphasis on the poorer parts of the world. We deliberately take a broad view of the complex interactions between climate change and global food security, stating what we do know with some degree of confidence, as well as acknowledging aspects where there is little or no evidence. We end by proposing a number of precepts for those making policy or practical decisions on climate change impacts and food security.

Food Security

Together, climate change and food security have multiple interrelated risks and uncertainties for societies and ecologies. The complexity of global food security is illustrated by the United Nations' Food and Agricultural Organization (FAO) (*6*) definition: (i) the availability of sufficient quantities of food of appropriate quality, supplied through domestic production or imports; (ii) access by individuals to adequate resources (entitlements) for acquiring appropriate foods for a nutritious diet; (iii) utilization of food through adequate diet, clean water, sanitation, and health care to reach a state of nutritional well-being where all physiological needs are met; and (iv) stability, because to be food secure, a population, household or individual must have access to adequate food at all times.

It is extremely challenging to assess precisely the current status of global food security from such a broad concept. However, the big picture is clear: About 2 billion of the global population of over 7 billion are food insecure because they fall short of one or several of FAO's dimensions of food security. Enormous geographic differences in the prevalence of hunger exist within this global estimate, with almost all countries in the most extreme "alarming" category situated in sub-Saharan Africa or South Asia (*7*) (Fig. 1).

Nevertheless, it is important to note that the current numbers for undernourished people are rough estimates at best and are seriously deficient in capturing the access, utilization, and stability dimensions of food security. First, the methods used to make these estimates only capture longer-term trends, not the short-term changes that can be an important consequence of climate variability. The most recent data are averages for the period 2010–2012 (*2*), so they do not capture a specific year, let alone shorter-term shocks, be they climate-related or otherwise. Second, they estimate calorie shortage only and do not cover other dietary deficiencies and related health effects that can impair physical and mental capacities. Third, they are derived from aggregate data, not actual household or individual-level food deficiencies, which hinders analyses of distributional effects of climate and other shocks. The FAO methodology was recently improved (*8*), but the above shortcomings could not be addressed within the framework of the current method, and thus, current analyses of climate change impacts on food security are incomplete. An overhaul of data-gathering methods that encompasses food deficiencies at household levels, as well as nutritional status, is needed.

Climate Change

There is a substantial body of evidence that shows that Earth has warmed since the middle of the 19th century (*9*–*14*). Global mean temperature has risen by 0.8°C since the 1850s, with the warming trend seen in three independent temperature records taken over land and seas and in ocean surface water (*15*). Climate change can result from natural causes, from human activities

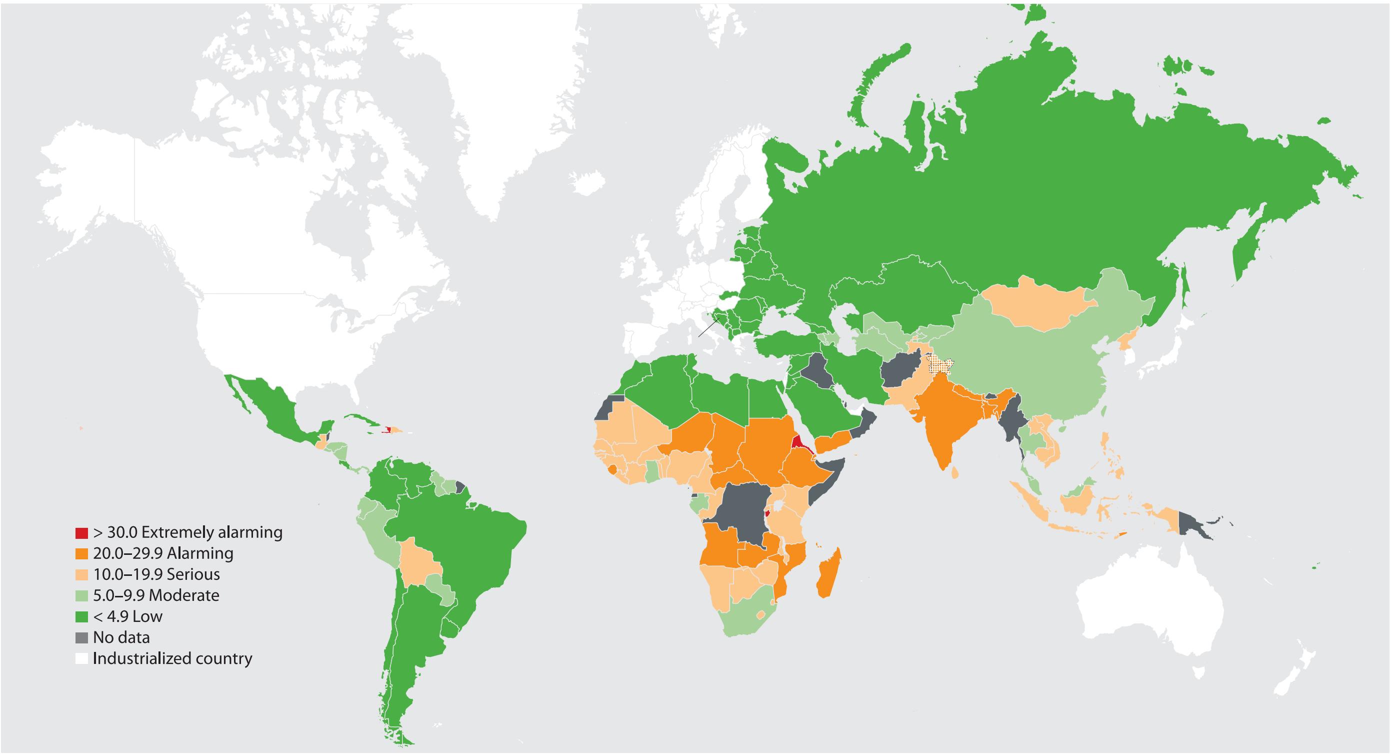

Fig. 1. Global distribution of hunger as quantified by the 2012 Global Hunger Index. The Welthungerhilfe, IFPRI, and Concern Worldwide Hunger map 2012 calculated a Global Hunger Index (*7*) for 120 countries by using the proportion of people who are undernourished, the proportion of children under 5 who are underweight, and the mortality rate of children younger than age 5, weighted equally. [Reproduced with permission from Welthungerhilfe, IFPRI, and Concern Worldwide (*7*)]

through the emission of greenhouse gases such as carbon dioxide and methane, and from changes in land use. Carbon dioxide (CO_2) levels in the atmosphere have increased from about 284 ppm in 1832 to 397 ppm in 2013 (*16*), and there is a theoretical link between the levels of such "greenhouse" gases in the atmosphere and global warming. Three independent reviews have found strong evidence for human causes for the observed temperature warming mainly caused by the burning of fossil fuels, with smaller contributions from land-use changes (*15*–*18*).

Thus, climate change is expected to bring warmer temperatures; changes to rainfall patterns; and increased frequency, and perhaps severity, of extreme weather. By the end of this century, the global mean temperature could be 1.8° to 4.0°C warmer than at the end of the previous century (*15*). Warming will not be even across the globe and is likely to be greater over land compared with oceans, toward the poles, and in arid regions (*15*). Recent weather records also show that land surface temperatures may be increasing more slowly than expected from climate models, potentially because of a higher level of absorption of CO_2 by deep oceans (*19*). Sea-level rises will increase the risk of flooding of agricultural land in coastal regions. Changes in rainfall patterns, particularly over tropical land, are less certain, partly because of the inability of the current models to represent the global hydrological cycle accurately (*20*). In general, it is expected that the summer Asian monsoon rainfall may increase, while parts of North and southern Africa could become drier (*15*). How will these regional changes in climate affect food security?

Research Biases

Agriculture is inherently sensitive to climate variability and change, as a result of either natural causes or human activities. Climate change caused by emissions of greenhouse gases is expected to directly influence crop production systems for food, feed, or fodder; to affect livestock health; and to alter the pattern and balance of trade of food and food products. These impacts will vary with the degree of warming and associated changes in rainfall patterns, as well as from one location to another.

Climate change could have a range of direct and indirect effects on all four dimensions of food security. How is the evidence base distributed across the dimensions of food security? We undertook a bibliographic analysis of peer-reviewed journal papers on food security and climate change since the publication of the first Intergovernmental Panel on Climate Change (IPCC) report in 1990 (*21*). That report was ground-breaking for the climate science that it reviewed, but agriculture was entirely absent. Our analysis shows that a small peak of papers with climate change and food security in the title or abstract were published in the mid-1990s, followed by a lull then a sharp increase in papers published with these terms from 2008 onward.

The distribution of the evidence across the four dimensions of food security is, however, heavily skewed toward food availability within 70% of the publications. Access, utilization, and stability dimensions of food security are represented by only 11.9, 13.9, and 4.2% of the total publications on food security and climate change, respectively.

Why is the evidence based on climate change impacts so unevenly distributed across the four dimensions of food security? There are several possibilities. Research has largely concentrated on the direct effects of climate change, such as those on crop growth and on the distribution of agricultural pests and diseases. Also, studies have understandably focused on areas that can be easily investigated, often through analyzing single-factor changes, and have avoided the complex and multilayered features of food security that require integrations of biophysical, economic, and social factors. Clearly, current knowledge of food security impacts of climate change is dramatically lacking in coverage across all dimensions of food security. Nevertheless, where there is good evidence, what are the broad conclusions?

Food Availability

Rosenzweig and Parry (*22*) produced the first global assessment of the potential impacts of climate change scenarios on crops. They used numerical crop models of wheat, rice, maize, and soybeans to simulate yields at 112 locations in 18 countries, in the current climate and under climate change using the output of three climate models. These point-based estimates of change

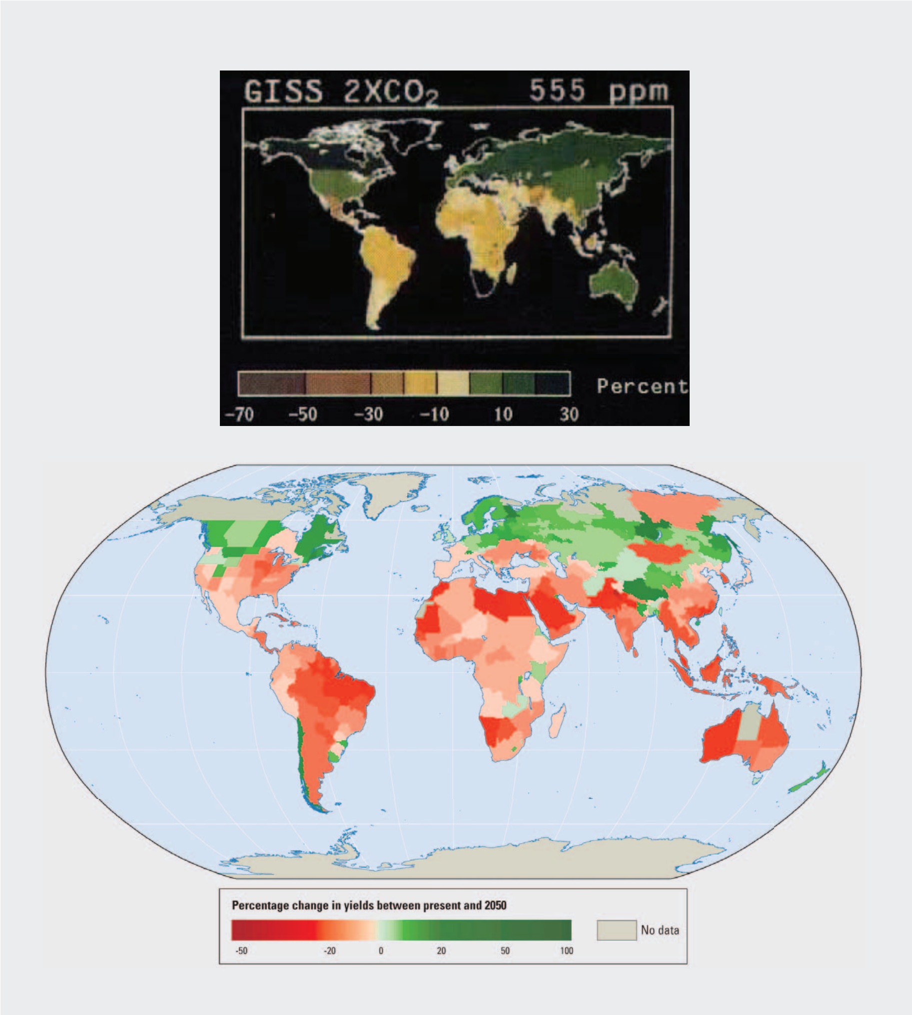

Fig. 2. Global impacts of climate change on crop productivity from simulations published in 1994 and 2010. (**Top**) The 1994 study (*22*) used output from the GISS GCM (in this example) with twice the baseline atmospheric CO_2 equivalent concentrations as input to crop models for wheat, maize, soybean, and rice that were run at 112 sites in 18 countries. Crop model outputs were aggregated to a national level using production statistics. (**Bottom**) The 2010 study (*27*) simulated changes in yields of 11 crops for the year 2050, averaged across three greenhouse emission scenarios and five GCMs. [Reprinted by permission from (top) Macmillan Publishers Ltd. (*22*); (bottom) World Bank Publishers (*27*)]

were then scaled-up to country level by using national crop production statistics. Future climate simulations under both present-day and doubled-CO_2 concentrations were used. They found that enhanced concentrations of atmospheric CO_2 increase the productivity of most crops through increasing the rate of leaf photosynthesis and improving the efficiency of water use. However, more recent research has proposed that the CO_2 yield enhancement in crop models is too large compared with observations of crop experiments under field conditions (*23*). If true, these revised estimates will affect the magnitude of the previous global crop yield changes but not the spatial distribution of impacts. Even if there is some debate on the magnitude of CO_2 effects, higher concentrations of CO_2 in the atmosphere are already having noticeable continental level effects on plant growth in sub-Saharan Africa (*24*).

The simulations of Rosenzweig and Parry (*22*) showed that there is a large degree of spatial variation in crop yields across the globe. Both the sign and magnitude of the projected changes in crop yield vary with alternative climate models and from one country to another. In general, yields increased in Northern Europe, but decreased across Africa and South America (*22*) (Fig. 2). Inevitably, there were methodological weaknesses in this study, including the use of only just over one hundred points to represent global crop production, the absence of any change in the areas suitable for crop production in future climates, limitations on how each of the model points is representative of their surrounding regions, and assumptions about varieties in the crop model parameters themselves. Nevertheless, as the first example of global impacts of climate change on crop production, these simulations are remarkable.

Since 1994, knowledge of the effects of climate on crop plant physiology has improved, the skill of simulation methods for climate change impact studies has increased, and better computing power and data sets to run global simulations have become available. Landmark studies since 1994 include those by Parry and colleagues (*25*), Cline (*26*), and, most recently, the World Bank (*27*) (Fig. 2). Specific projections vary with the climate model scenario used, the simulations methods, and the time scale over which the projections are done. However, the broad-scale pattern of climate change impacts on crop productivity and production has remained consistent across all of these global studies spanning almost 20 years of research. Crop yields are more negatively affected across most tropical areas than at higher latitudes, and impacts become more severe with an increasing degree of climate change. Furthermore, large parts of the world where crop productivity is expected to decline under climate change (Fig. 2) coincide with countries that currently have a high burden of hunger (Fig. 1). We conclude that there is a robust and coherent pattern on a global scale of the impacts of climate change on crop productivity and, hence, on food availability and that climate change will exacerbate food insecurity in areas that already currently have a high prevalence of hunger and undernutrition.

A recent systematic review of changes in the yields of the major crops grown across Africa and South Asia under climate change found that average crop yields may decline across both regions by 8% by the 2050s (*28*). Across Africa, yields are predicted to change by –17% (wheat), –5% (maize), –15% (sorghum), and –10% (millet) and, across South Asia, by –16% (maize) and –11% (sorghum) under climate change. No mean change in yield was detected for rice. Knox *et al.* (*28*) concluded that evidence for the impact of climate change on crop productivity in Africa and South Asia is robust for wheat, maize, sorghum, and millet, and inconclusive, absent, or contradictory for rice, cassava, and sugarcane.

Global-scale climate change impacts at a grid scale of 200 to 250 km can provide useful information on shifts in production zones and perhaps guide the focus of global crop improvement programs seeking to develop better-adapted crop varieties. However, much of the adaptation of agricultural practice to climate change will be driven by decisions at the farm and farm-enterprise scale. These decisions need much finer resolution information than that shown in Fig. 2. At much finer grid scales of 5 to 20 km there are even greater limits to the skill of predictive crop science than at the global scale. Additional uncertainties arise from how the output of global-scale climate models is down-scaled, whether input data (such as crop, soil, topographic, and management information) are available across the domain for crop simulation at this scale, as well as questions as to how skillful the simulation methods are across a fine-scale domain. Recent attempts to harmonize modeling approaches for wheat simulations under climate change found considerable variation in projected impacts among models owing to differences in model structures and parameter values (*29*). It is not surprising that the sheer complexity of food production systems at a very fine scale is difficult to reproduce in numerical models. However, there is a real need for studies that test how well fine-scale simulations compare with observations in the current climate, as a necessary test of their utility in future climates.

Although the evidence for direct climate change effects on crop productivity is reasonable, important limitations remain for impacts on food availability more broadly. First, models that adequately capture expected climate change effects on crops are only available for the major cereals, groundnut, and some roots and tubers. Impacts on other important crops (such as vegetables, pulses, and locally important, but globally minor, crops) are often inferred based on similar plant characteristics, rather than studied explicitly. Second, changes in grassland productivity and grazing quality and the quality of crops for livestock feed (*30*) have hardly been captured, which limits the understanding of climate change–livestock linkages. Last, many crop studies capture the impacts of mean changes in climate, but are less accurate for changes in weather extremes, which can have even more important consequences for crop yields (*31*).

Food Access

Food access (and utilization) connects to climate change through indirect, but well-known, pathways. Access to food is largely a matter of household and individual-level income and of capabilities and rights. Food access issues have been studied through two types of approaches: top-down by models that attempt to link macro-shocks to household level responses and adaptation outcomes; and by community- and household-level studies that try to assess climate change effects from the bottom up.

The macro-modelsare often composed of interlinked models—including climate, crop, and economic models. In this approach, outcomes from a climate model feed into the crop model to simulate crop yields under different climate scenarios. The simulated yields are then used to make economic forecasts for the impact of climate change on prices, incomes, trade, and such like. The macro-models can either be constructed following a partial equilibrium approach, i.e., studying the impacts only in one specific sector, such as agriculture, or as general equilibrium models seeking to capture the impacts on the whole economy. The weakness of this approach is that it barely captures climate adaptations. In contrast, micro-level studies are often based on detailed household surveys and usually better account for adaptation by households and communities to climate change.

An important example is the International Food Policy Research Institute (IFPRI) International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model, which connects climate change scenarios with food supply effects and market and price outcomes, and traces the economic consequences of food availability drivers to access and utilization of food, that is, food energy consumption and children's nutritional situation (*32*, *33*). Specific findings are heavily dependent on the assumptions made about future income and population growth but, in general, show clear linkages between economic growth and resilience to climate change (*32*).

A host of studies is emerging that analyzes what happens to communities and households when they are exposed to climate shocks (*34*–*37*). These approaches tend to capture more adaptation capabilities than macro-models, such as asset draw-down, job-switching, migration, social policy responses, and collective action for adaptation and assistance. But it is difficult to appropriately capture with micro-level studies the covariate risks of climate change that cut across broad regions.

Climate change could transform the ability to produce certain products at regional and international levels. If it turns out, for example, that the geography of biomass production shifts at a global scale (*38*), this will have production implications for all bio-based products—whether food, feed, fuels, or fiber—and will impinge on food trade flows, with implications for (farm) incomes and access to food (*39*). Similar changes have been observed in the geography and relative productivity of certain ocean species, such as shifts between anchovy and sardine regimes in the Pacific Ocean (*40*).

Thus, macro-modeling and micro-level analyses of climate change linkages to food security are complementary. The prices of the basic resources, such as land and water, are formed by long-term expectations (*41*, *42*), and these prices encompass expectations of climate change, such as revaluation of land with access to water. Structural consequences can emerge, particularly when property rights are lacking and traditional land and water rights are not protected, as is the case in many developing countries with food security problems (*43*–*45*); these structural problems lead to erosion of the assets of the poor, as seen during "land grabbing" by external and foreign interests (*46*).

Food Utilization

Food utilization, to attain nutritional well-being, depends upon water and sanitation and will be affected by any impact of climate change on the health environment. Little research has been done on this dimension of food and nutrition security. Links with drinking water may be obvious, when climate variability stresses clean drinking water availability (*47*, *48*). Hygiene may also be affected by extreme weather events causing flooding or drought in environments where sound sanitation is absent (*49*–*51*). In addition, uptake of micronutrients is adversely affected by the prevalence of diarrheal diseases, which in turn is strongly correlated with temperature (*52*).

Climate change can also impinge on diet quality, and increased costs may result from measures required to avoid food contamination stemming from ecological shifts of pests and diseases of stored crops or food (*53*, *54*). Science and innovation have a role to play here, and in recent years there has been good progress made in improving food utilization through fortification and biofortification (*55*, *56*). Vulnerability to food security shocks needs further research, as do ways to strengthen adaptive capacities under climate change, (*57*) as public policy responses depend on such insights. For example, appropriate design of programs transferring income to the poor, employment-related transfer programs, and early childhood nutrition actions (*58*–*60*) may all need expanding to respond to climate-related volatilities.

New nutritional stresses are emerging, and the most striking example has been the recent "nutrition transition," i.e., the process by which globalization, urbanization, and changes in lifestyle are linked to excess caloric intake, poor-quality diets, and low physical activity. Together, these factors have led to rapid rises in the incidence of obesity and chronic diseases, even among the poor, in developing countries (*61*). The nutrition transition will unfold in parallel with climate change in coming decades, but very little research on the potentially reinforcing effects of these phenomena has been done.

Stability of the Food System

The stability of whole food systems may be at risk under climate change, as climate can be an important determinant for future price trends (*32*), as well as the short-term variability of prices. Since 2007, the world food equation has been at a precariously low level and, consequently, even small shocks on the supply or demand side of the equation will have large impacts on prices, as experienced in 2008 (*62*). Food security of the poor is strongly affected by staple food prices, as a large part of an impoverished family's income has to be spent on staple foods.

Climate change is likely to increase food market volatility for both production and supply [see (*63*) for the supply side]. Food system stability can also be endangered by demand shocks, for instance, when aggressive bioenergy subsidies and quota policies were applied by the political economy (*64*). These sorts of policy shifts, made in the past decade by the United States and the European Union, have been motivated in part by energy security concerns and partly by climate mitigation objectives (*65*–*67*). The resulting destabilization of food markets, which contributed to major food security problems, was therefore partly related to climate change (policy).

The 2008 food crisis stemmed from a combination of a general reduction of agricultural productivity and acute policy failures, exacerbated by export restrictions applied by many countries, a lack of transparency in markets, and poor regulation of financial engagement in food commodity markets (*68*, *69*). A broad set of risks needs to be considered, of which climate change is an increasingly important one, that can ripple out to destabilize food systems, resulting in high and volatile food prices that temporarily limit poor people's food consumption (*70*–*73*), financial and economic shocks that lead to job loss and credit constraints (*74*), and risks that political disruptions and failed political systems cause food insecurity (*75*). This complex system of risks can assume a variety of patterns that could potentially collide in catastrophic combinations.

What We Need to Know—Research and Evidence Gaps

Despite a burgeoning literature over the past 5 years or so, much remains unknown about many food security impacts of climate change. Getting better evidence will help to some extent. For example, uncertainties in understanding the underlying science, social science, and economics of climate change impacts will reduce as the evidence base expands with more research. However, other uncertainties will always remain as they arise from projections of climate change, sources of natural variability in climate, and future pathways of emissions of greenhouse gases.

Four broad priorities for future research emerge from our review: (i) gathering evidence on the effects of climate change impacts on the food access, utilization, and stability dimensions in order to achieve a more holistic understanding of food security; (ii) understanding the indirect impacts of climate change on food security requires more comprehensive analytical approaches and sophisticated modeling, including links to the political economy; (iii) improving projections of regional climate change effects on food security at country level and on smaller scales that are crucial for decision-making for adaptation of food systems; (iv) better integrating of human dimensions of climate change impacts into food security planning—because food systems are ultimately driven by people and their behavioural responses to real and perceived changes in their local climate—that will be central to the adaptation to climate change and actions to address hunger.

What We Know We Know—Messages for Decision-Makers

Decisions still need to be taken by policy-makers and practitioners confronted with the prospect of climate change impacts on food security, despite very real uncertainties in current knowledge and future trends. For those making decisions, we propose, with a fair degree of confidence from the existing evidence, six precepts for the impacts of climate change on food security:

1) Climate change impacts on food security will be worst in countries already suffering high levels of hunger and will worsen over time.

2) The consequences for global undernutrition and malnutrition of doing nothing in response to climate change are potentially large and will increase over time.

3) Food inequalities will increase, from local to global levels, because the degree of climate change and the extent of its effects on people will differ from one part of the world to another, from one community to the next, and between rural and urban areas.

4) People and communities who are vulnerable to the effects of extreme weather now will become more vulnerable in the future and less resilient to climate shocks.

5) There is a commitment to climate change of 20 to 30 years into the future as a result of past emissions of greenhouse gases that necessitates immediate adaptation actions to address global food insecurity over the next two to three decades.

6) Extreme weather events are likely to become more frequent in the future and will increase risks and uncertainties within the global food system.

All of these precepts support the need for considerable investment in adaptation and mitigation actions to prevent the impacts of climate change from slowing progress in eradicating global hunger and undernutrition. A wide range of potential adaptation and resilience options exist and more are being developed. These need to address food security in its broadest sense and to be integrated into the development of agriculture worldwide. Building agricultural resilience, or "climate-smart agriculture," through improvements in technology and management systems is a key part of this, but will not be sufficient on its own to achieve global food security. The whole food system needs to adjust to climate change, with strong attention also to trade, stocks, and to nutrition and social policy options. We need to work toward what could be termed a climate-smart food system that addresses climate change impacts on all dimensions of food security.

References and Notes

1. K. Ban, A message from the UN Secretary General for the opening session of the 39th Session of the Committee on World Food Security, Rome, 15 to 20 October 2012; www.un-foodsecurity.org/node/1356.
2. FAO, World Food Programme, International Fund for Agricultural Development, *The State of Food Insecurity in the World 2012: Economic Growth Is Necessary But Not Sufficient to Accelerate Reduction of Hunger and Malnutrition* (FAO, Rome, 2012); www.fao.org/docrep/016/i3027e/i3027e00.htm.
3. J. Bruinsma, *World Agriculture: Towards 2015/2030: An FAO Perspective* (Earthscan, London, 2003).
4. T. Garnett *et al.*, *Science* **341**, 33–34 (2013).
5. High-Level Panel of Experts on Food Security and Nutrition (HLPE), *Food Security and Climate Change: A Report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security* (HLPE, report no. 3, HLPE, Rome, 2012 (2012).
6. FAO, Rome declaration on world food security and World Food Summit plan of action, World Food Summit, Rome, 13 to 17 November 1996.
7. K. von Grebmer *et al.*, *2012 Global Hunger Index: The Challenge of Hunger: Ensuring Sustainable Food Security Under Land, Water, and Energy Stresses* (Welthungerhilfe, IFPRI, Concern Worldwide, 2012); www.ifpri.org/publication/2012-global-hunger-index-0.
8. FAO, Technical Note: FAO Methodology to estimate the prevalence of undernourishment (FAO, Rome, 2012); www.fao.org/fileadmin/templates/es/SOFI_2012/sofi_technical_note.pdf.
9. R. Böhm *et al.*, *Clim. Change* **101**, 41–67 (2010).
10. J. Hansen, R. Ruedy, M. Sato, K. Lo, *Rev. Geophys.* **48**, RG4004 (2010).
11. R. Rohde *et al.*, *Geoinfor Geostat. Overview* **1**, 1 (2013).
12. C. Rosenzweig *et al.*, in *Climate Change 2007: Impacts, Adaptation and Vulnerability*: *Contribution of Working Group II to the Fourth Assessment Report of the IPCC*, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, C. E. Hanson, Eds. (Cambridge Univ. Press, Cambridge, 2007), pp. 79–131.
13. M. E. Mann *et al.*, *Science* **326**, 1256–1260 (2009).
14. J. A. Screen, I. Simmonds, *Nature* **464**, 1334–1337 (2010).
15. S. Solomon *et al.*, in *Climate Change 2007: The Physical Science Basis*: *Contribution of Working Group I to the Fourth Assessment Report of the IPCC*, S. Solomon *et al.*, Eds. (Cambridge Univ. Press, New York, 2007), pp. 1–8.
16. P. Tans, R. Keeling, Trends in Atmospheric CO_2 at Mauna Loa, Hawaii (Earth System Research Laboratory, National Oceanic and Atmospheric Administration and Scripps Institution of Oceanography, La Jolla, CA, 2013); www.esrl.noaa.gov/gmd/ccgg/trends/.
17. Royal Society, *Climate Change: A Summary of the Science* (Royal Society, London, 2010).
18. Committee on America's Climate Choices; National Research Council, *America's Climate Choices* (National Academies Press, Washington, DC, 2011).
19. M. A. Balmaseda, K. E. Trenberth, E. Källén, *Geophys. Res. Lett.* **40**, 1754–1759 (2013).
20. C. Lorenz, H. Kunstmann, *J. Hydrometeorol.* **13**, 1397–1420 (2012).
21. The database of the Centre for Agricultural Bioscience International (CABI) was searched from 1990 to 2012 for journal papers that had "food security" AND "climate change" in the title. Within this group, the abstract was searched for terms related to food availability ("crop AND yield" OR "crop AND production" OR "livestock AND yield" OR "livestock AND production"), access ("access" OR "allocation" OR "safety"), utilization ("nutrition" OR "utilization") and stability ("affordability" OR "stability"). Note that the total of 260 papers found does not represent all papers published on any individual dimension of food security during this period, just those with food security and climate change in the title. For example, we found 310 papers with "crop AND yield" OR "crop AND production" from 1990 to 2012. It is also interesting to see peaks of these papers occurring 4 years after the publication of each of the IPCC reports in 1990, 1995, 2001, and 2007.
22. C. Rosenzweig, M. L. Parry, *Nature* **367**, 133–138 (1994).
23. S. P. Long, E. A. Ainsworth, A. D. B. Leakey, J. Nösberger, D. R. Ort, *Science* **312**, 1918–1921 (2006).
24. P. Vlek, Q. B. Le, L. Tamene, in *Food Security and Soil Quality*, R. Lal, B. A. Stewart, Eds. (CRC Press, Boca Raton, FL, 2010), pp. 57–86.
25. M. L. Parry, C. Rosenzweig, A. Iglesias, M. Livermore, G. Fischer, *Glob. Environ. Change* **14**, 53–67 (2004).
26. W. R. Cline, *Global Warming and Agriculture*: *Impact Estimates by Country* (Center for Global Development, Peterson Institute for International Economics, Washington, DC, 2007).
27. World Bank, "World Bank development report 2010: Development and climate change" (World Bank, Washington, DC, 2010).
28. J. Knox, T. Hess, A. Daccache, T. Wheeler, *Environ. Res. Lett.* **7**, 034032 (2012).
29. S. Asseng *et al.*, *Nat. Clim. Change* 10.1038/nclimate1916 (2013).
30. T. Wheeler, C. Reynolds, *Anim. Front.* **3**, 36–41 (2013).
31. T. R. Wheeler, P. Q. Craufurd, R. H. Ellis, J. R. Porter, P. V. Vara Prasad, *Agric. Ecosyst. Environ.* **82**, 159–167 (2000).
32. G. C. Nelson *et al.*, *Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options* (IFPRI, Washington, DC, 2010).
33. C. Ringler *et al.*, *How Can African Agriculture Adapt to Climate Change? Insights from Ethiopia and South Africa* (IFPRI, Washington, DC, 2011).
34. K. Kato, C. Ringler, M. Yesuf, E. Bryan, *Agric. Econ.* **42**, 593–604 (2011).
35. S. Silvestri, E. Bryan, C. Ringler, M. Herrero, B. Okoba, *Reg. Environ. Change* **12**, 791–802 (2012).
36. S. L. M. Trærup, *Glob. Environ. Change* **22**, 255–267 (2012).
37. A. Mirzabaev, thesis, Center for Development Research, University of Bonn (2013).
38. M. Zhao, S. W. Running, *Science* **329**, 940–943 (2010).
39. T. W. Hertel, M. B. Burke, D. B. Lobell, *Glob. Environ. Change* **20**, 577–585 (2010).
40. F. P. Chavez, J. Ryan, S. E. Lluch-Cota, M. Niquen C, *Science* **299**, 217–221 (2003).
41. A. M. Michelsen, J. F. Booker, P. Person, *Int. J. Water Resour. Dev.* **16**, 209–219 (2000).
42. T. T. Phipps, *Am. J. Agric. Econ.* **66**, 422 (1984).
43. D. Maxwell, K. Wiebe, *Dev. Change* **30**, 825–849 (1999).
44. K. Deininger, G. Feder, *World Bank Res. Obs.* **24**, 233–266 (2009).
45. H. C. J. Godfray *et al.*, *Science* **327**, 812–818 (2010).
46. A. Arezeki, K. Deininger, H. Selod, "What drives the global land rush?" (Policy research working paper 5864, World Bank, Washington, DC, 2011); http://elibrary.worldbank.org/content/workingpaper/10.1596/1813-9450-5864.
47. Z. W. Kundzewicz *et al.*, in *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the IPCC*, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, C. E. Hanson, Eds. (Cambridge Univ. Press, Cambridge, 2007), pp. 173–210.
48. I. Delpla, A. V. Jung, E. Baures, M. Clement, O. Thomas, *Environ. Int.* **35**, 1225–1233 (2009).
49. D. C. Griffith, L. A. Kelly-Hope, M. A. Miller, *Am. J. Trop. Med. Hyg.* **75**, 973–977 (2006).
50. M. Hashizume *et al.*, *J. Water Health* **6**, 323–332 (2008).
51. A. C. Shimi, G. A. Parvin, C. Biswas, R. Shaw, *Disaster Prev. Manag.* **19**, 298–313 (2010).
52. J. Schmidhuber, F. N. Tubiello, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 19703–19708 (2007).
53. R. R. M. Paterson, N. Lima, *Food Res. Int.* **43**, 1902–1914 (2010).
54. T. Tefera, *Food Security* **4**, 267–277 (2012).
55. H. E. Bouis, *Proc. Nutr. Soc.* **62**, 403–411 (2003).
56. P. Nestel, H. E. Bouis, J. V. Meenakshi, W. Pfeiffer, *J. Nutr.* **136**, 1064–1067 (2006).
57. G. Ziervogel, P. J. Ericksen, *WIREs Clim Change* **1**, 525–540 (2010).
58. M. Niño-Zarazúa, A. Barrientos, S. Hickey, D. Hulme, *World Dev.* **40**, 163–176 (2012).
59. A. Barrientos, D. Hulme, Eds., *Social Protection for the Poor and Poorest—Concepts, Policies and Politics* (Palgrave Macmillan, New York, 2008).
60. B. L. Rogers, J. Coates, "Food-based safety nets and related programs" (Social Protection Discussion paper 225, World Bank, Washington, DC, 2002).
61. B. M. Popkin, L. S. Adair, S. W. Ng, *Nutr. Rev.* **70**, 3–21 (2012).
62. J. von Braun, *Food Security* **1**, 9–15 (2009).
63. L. O. Mearns, C. Rosenzweig, R. Goldberg, *Clim. Change* **32**, 257–292 (1996).
64. J. Beckman, T. Hertel, F. Taheripour, W. Tyner, *Eur. Rev. Agric. Econ.* **39**, 137–156 (2012).
65. European Commission, Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport (published 17.5.2003, Official Journal of the European Union, pp. L123/42–46) (2003).
66. U.S. Congress, Energy Policy Act of 2005, Public Law 109, 58 (42 USC 15801 note), 109th Congress, 8 August 2005.
67. U.S. Congress, Energy Independence and Security Act of 2007, Public Law 110-140 (42 USC 17001 note), 110th Congress, 19 December 2007.
68. J. von Braun, G. Tadesse, in *Institutions and Comparative Economic Development*, A. Masahiko, T. Kuran, G. Roland, Eds. (International Economic Association Conference vol. 150-I, Palgrave Macmillan, London, 2012), pp. 298–312.
69. D. Headey, S. Fan, *Agric. Econ.* **39**, 375–391 (2008).
70. C. Arndt, M. A. Hussain, L. P. Østerdal, "Effects of food price shocks on child malnutrition: The Mozambican experience 2008/09" (UN Univ.—World Institute for Development Economics Research Working paper 2012/89, UN Univ., Helsinki, 2012).
71. A. A. Campbell *et al.*, *J. Nutr.* **140**, 189S–194S (2010).
72. A. de Brauw, *Food Policy* **36**, 28–40 (2011).
73. H. Torlesse, L. Kiess, M. W. Bloem, *J. Nutr.* **133**, 1320–1325 (2003).
74. J. P. Smith, D. Thomas, E. Frankenberg, K. Beegle, G. Teruel, *J. Popul. Econ.* **15**, 161–193 (2002).
75. J. Berazneva, D. R. Lee, *Food Policy* **39**, 28–39 (2013).

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