# Closing Yield Gaps: Consequences for the Global Food Supply, Environmental Quality & Food Security

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*Abstract: The social, economic, and environmental costs of feeding a burgeoning and increasingly affluent human population will depend, in part, on how we increase crop production on under-yielding agricultural landscapes, and by how much. Such areas have a "yield gap" between the crop yields they achieve and the crop yields that could be achieved under more intensive management. Crop yield gaps have received increased attention in recent years due to concerns over land scarcity, stagnating crop yield trends in some important agricultural areas, and large projected increases in food demand. Recent analyses of global data sets and results from field trials have improved our understanding of where yield gaps exist and their potential contribution to increasing the food supply. Achieving yield gap closure is a complex task: while agronomic approaches to closing yield gaps are generally well-known, a variety of social, political, and economic factors allow them to persist. The degree to which closing yield gaps will lead to greater food security and environmental benefits remains unclear, and will be strongly influenced by the particular strategies adopted.*

The grand challenge of feeding a growing global population will require a diversity of solutions if we are to simultaneously protect natural resources and enhance food security. One frequently cited strategy is to increase food production on existing agricultural lands: the continued "intensification" of agriculture.[1] Increasing productivity has the potential to augment food supply while sparing natural ecosystems from conversion to agriculture.[2] Much of the worlds' croplands have experienced growth in crop yields (production per unit area), beginning, perhaps most dramatically, with the advent of green revolution technologies during the mid-twentieth century. However, not all regions have uniformly achieved gains; in many areas, a *yield gap* persists between the crop yields that are achieved and the crop yields that are achievable using the right cultivars, inputs, and other management practices.

Because yield gaps are the end result of myriad interacting biological, physical, and economic forces,

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the conceptual simplicity of the yield gap is deceptive. Plant breeders develop new crop varieties, seeking both to increase potential yields and remain one step ahead of continuously evolving pests and diseases. Farmers operate within geographic and financial constraints, seeking to make the best decisions possible – not always maximization of yield – in the context of local policies, markets, and infrastructure.

Efforts to close yield gaps – or simply understand their existence – must engage with these complexities. In this essay, we attempt to do so. To begin, we discuss the increased scientific attention on yield gaps in recent years, and why closing yield gaps through agricultural development may be critical for the future of the global food supply. We continue by describing recent efforts to quantify yield gaps: their magnitudes, spatial distribution, and potential contributions toward meeting future food demand. We then explore from agronomic and socioeconomic perspectives how yield gaps may be "closed" and the potential consequences of these changes for food security and the global environment.

While yield gaps have been described and documented by agricultural scientists for decades, scrutiny of the topic in the agriculture-environment research community has increased in recent years due to concerns about land scarcity.[3] Cropland and pasture systems already have a massive land footprint, replacing natural ecosystems across nearly 40 percent of the earth's ice-free land.[4] While land conversion for agriculture has slowed, it remains a major source of greenhouse gas emissions and a critical threat to biodiversity.[5] Pressure for continued conversion will only build if the demands of a growing and increasingly affluent population outstrip the rate of improvement in crop yields.

In fact, steadily increasing crop yields in many of our most important agricultural regions can no longer be taken for granted. A recent analysis of 2.5 million yield observations from national agricultural census records documented widespread stagnation of yield growth across 24 – 39 percent of global maize, wheat, rice, and soybean areas.[6] Other studies using alternate analytical approaches and data sets have arrived at similar conclusions, showing stagnant areas across wide swathes of both developing and developed countries.[7] Areas of stagnant wheat and rice yield are of particular concern; unlike maize and soybean, the vast majority of wheat and rice production feeds people, not livestock.[8] Hotspots of stagnation include France (79 percent of harvested wheat area), China (79 percent of harvested rice area), and India (70 percent of harvested rice area).[9]

While yield growth has begun to stagnate, growth in food demand is expected to accelerate. In the recent past, most food supply increases were met by greater production on existing agricultural lands. Between 1985 and 2005, crop production increased approximately 28 percent while the land footprint of global croplands increased by only 2.4 percent, due to crop yield increases of nearly 20 percent and an increase in harvest frequency (due to multi-cropping and a decrease in fallowed area) of approximately 7 percent.[10] However, with rising incomes in developing nations and the increased adoption of diets rich in animal products, demand for food and feed from global croplands is expected to roughly double between 2005 and 2050.[11]

The prospect of increasing global food scarcity poses both a challenge and an opportunity for low- and middle-income nations, where the interest in closing yield gaps has been motivated by the potential for enhanced agricultural productivity to alleviate poverty and spur economic development. Growth in the agricultural sector, it is widely believed, is an important catalyst for broader economic growth in many developing countries, where agriculture directly or indirectly supports the livelihoods of more than two billion people. If policy intervention can enable under-yielding farmers to intensify production profitably – without incurring substantial additional risk – then closing yield gaps could go hand-in-hand with supporting the livelihoods and ensuring the food security of some of the world's poorest populations.

Recent efforts have quantified and identified global patterns in yield gaps, creating the foundation upon which to explore the possibilities and consequences of geographically targeted initiatives to enhance yields. The ability to assess yield gaps at the global scale improved dramatically in 2008, with the release of a data set of crop-harvested area and yield information created by sustainability scientist Chad Monfreda and colleagues. This data set fuses remote sensing and national agricultural census reports published circa 2000.[12] Much of the census data collection was undertaken through the Agro-MAPS project, a collaboration between the United Nations Food and Agriculture Organization, the International Food Policy Research Institute, and the Center for Sustainability and the Global Environment at the University of Wisconsin. The Monfreda data set has informed three analyses of global yield gaps, which largely agree on the spatial distribution of yield gaps and the potential of closing yield gaps to increase the global food supply.[13]

Global yield gap studies use sampling or statistical methods to provide a landscape-scale estimate of best-in-class yields (also known as "attainable yields"). As these studies use census data – which are aggregated and averaged across space to some degree – they do not predict the absolute biophysical "potential yield" of a crop that is grown without any management limitations. Such values are more often derived from field trials and crop simulation computer models.[14] The global studies also calculate potential yields using average climate and average yields; in contrast, local studies may calculate the unique yield potentials for growing conditions in each year. To incorporate chronic water limitation into yield gap analyses, local and regional studies often calculate potential yields separately for rainfed (often called "water-limited yield potential") and irrigated conditions. In the case of the global study by Mueller and colleagues, crop-specific irrigation data and a statistical approach were used to identify maximum rainfed yields.[15]

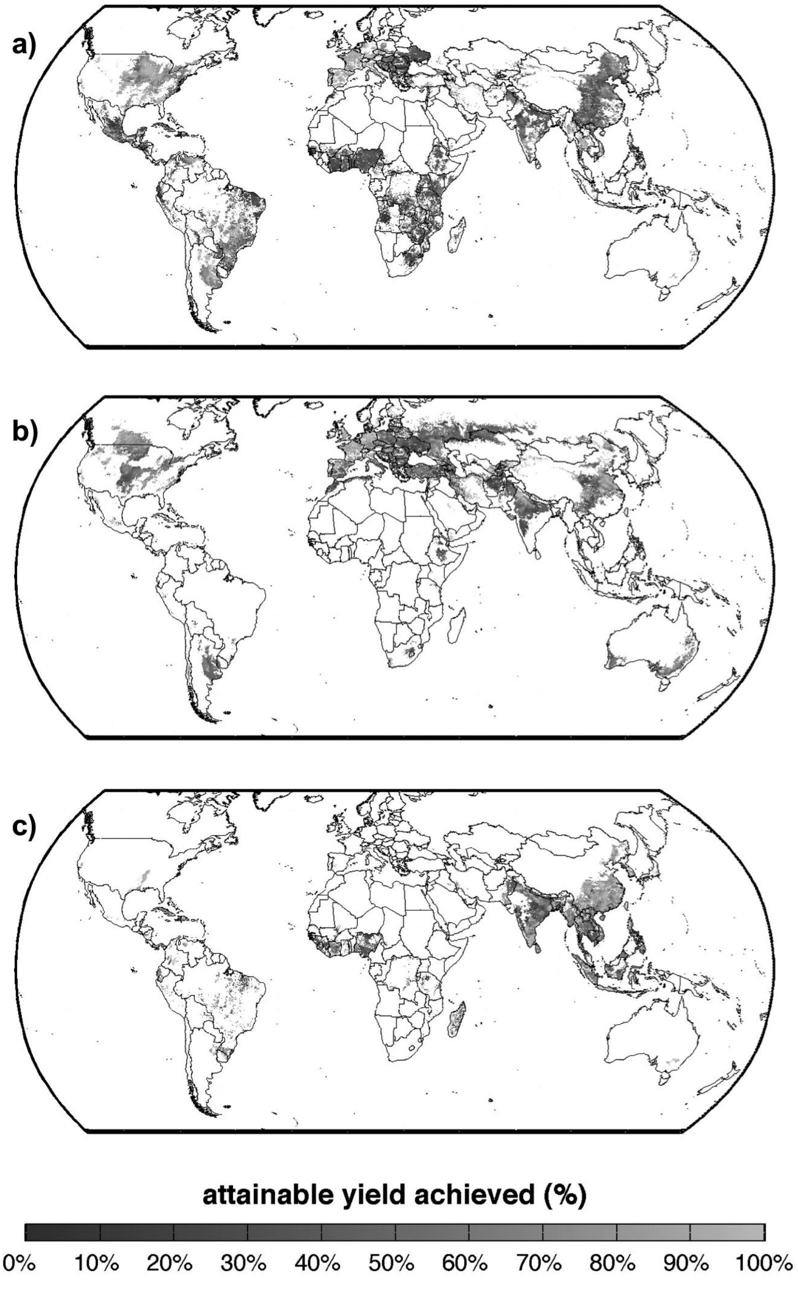
The potential contributions of closing yield gaps to the food supply are substantial. With colleagues, we have previously estimated that complete closure of yield gaps (to best-in-class yields within climate zones) could increase production by 45–70 percent for most of the seventeen crops we examined.[16] For maize, wheat, and rice, the potential production changes were estimated at 64 percent, 71 percent, and 47 percent, respectively. A report by the Australian Centre for International Agricultural Research (ACIAR) has scaled up field-level yield gap assessments, estimating potential production changes of 98 percent, 50 percent, and 71 percent for maize, wheat, and rice, respectively.[17] Differences between the estimates are unsurprising, given the divergent methodological approaches. However, both sets of results suggest that efforts to close yield gaps are necessary – but insufficient – to meet the expected doubling of future food demand. Enhancing crop yield potential through breeding, decreasing food waste, and shifting diets are other important leverage strategies that could increase total food availability and improve sustainability of the food system.

Generally speaking, the largest yield gaps exist in sub-Saharan Africa (SSA), Eastern Europe and Russia, and South Asia. Maize yield gaps in SSA are some of the world's largest: yields circa 2000 were around one and a half tons per hectare, while attainable yields across maize-growing areas in SSA were estimated to be around five tons per hectare. These "top-down" estimates are relatively consistent with the "bottom-up" estimates of the ACIAR, which reports farm yields of around one and a half tons per hectare for both East and West Africa, and potential yield estimates of seven and five tons per hectare, respectively. It is also expected that Eastern Europe and Russia could realize large increases in wheat production from closing yield gaps. Kathleen Neumann, a scholar of human-environmental interactions, and colleagues have estimated wheat yield gaps of one to three tons per hectare across most of the region, consistent with our estimates of attainable yields around four and a half tons per hectare and yields of two tons per hectare, circa 2000. In South Asia, extensive regions of wheat and rice cultivation with moderate yield gaps create large possibilities for production increases. Moderate yield gaps for maize in East Asia, along with large harvested areas, create a similar production opportunity in that region. While maize yields in China are around five tons per hectare, researchers estimate attainable yields to be between nine and ten and a half tons per hectare. The spatial patterns of yield gaps are visualized for maize, wheat, and rice in Figure 1.

Looking forward, opportunities are increasing to enhance our understanding of yield gaps at the global scale, in part due to increasing data availability. One promising development is the independent data collection and processing effort by International Food Policy Research Institute scientist Liangzhi You and colleagues, which has produced new maps of crop-harvested area and yield.[18] As the data set utilizes an independent collection of census statistics and different assumptions to disaggregate the census information down to individual grid cells, new analyses with this data set are helping us understand the sensitivity of yield gap calculations to different source data.[19] Additionally, the data set produced by University of Minnesota Global Landscapes Initiative senior scientist Deepak Ray and colleagues to analyze crop yield trends provides enhanced temporal resolution, and now contains approximately 2.5 million observations, from 1961 – 2008, for maize, wheat, rice, and soybean.[20] Analyses with this data set will allow us a greater understanding of how both yield potentials and yield gaps have changed over time. Efforts are also underway – under the banner of the Global Yield Gap Atlas project – to scale up yield gap estimates derived from process-based crop models.[21] These models simulate crop growth and development over the course of a growing season. They are sensitive to planting and harvest times, daily weather variations, fine-scale soil conditions, and characteristics of particular crop varieties. While these models are often successful at simulating yields at the field or farm level, they are not as often applied at larger scales. The Global Yield Gap Atlas project seeks to fill this gap, and eventually, all of these new efforts will improve our understanding of yield gaps at both local and global scales.

Even as the science paints an increasingly detailed picture of the type, extent, and global distribution of yield gaps, understanding *why* yield gaps exist (and persist) presents a critical challenge to developing appropriate and effective solutions to the related problems of food scarcity, food insecurity, and environmental degradation. The determinants of yield gaps are as much social as they are environmental. Sociopolitical and economic conditions, which influence farmer decision-making, drive which management practices are adopted; in turn, a variety of these management practices, alongside local environmental factors, in-

*Figure 1*
Estimated Yield Gaps circa 2000 for Maize, Wheat, and Rice



Yield gaps for maize (A), wheat (B), and rice (C) presented as the percent of attainable yields achieved. Source: Nathaniel D. Mueller, James S. Gerber, Matt Johnston, Deepak K. Ray, Navin Ramankutty, and Jonathan A. Foley, "Closing Yield Gaps through Nutrient and Water Management," *Nature* 490 (2012): 254 – 257.

fluence the biophysical growing conditions experienced by a particular crop during its development.

Agricultural scientists have amassed a sound understanding of the biophysical factors that can limit yields. Planting and harvest dates, crop variety, and planting density all influence the yield potential a crop can achieve in a given environment.[22] As the plant develops, deficiencies in growing conditions may lead to a yield gap. Moisture may either be limiting (causing water stress) or in excess (leading to waterlogged soils). Critical micronutrients or macronutrients (nitrogen, phosphorus, and potassium) can limit plant growth. Inadequate soil conditions, such as low organic matter content or undesirable pH, may limit yields (if not ameliorated by the farmer). Weeds, diseases, pests, and even atmospheric pollutants (such as tropospheric ozone) can also lead to yield losses.[23]

The relative contribution of these factors to existing yield gaps is an area of active research. Global studies using statistical models have, not surprisingly, confirmed the importance of fertilizers and irrigation as major controls on existing yield gaps.[24] Enhanced resolution at the regional scale is made possible by administering surveys to agricultural experts in different cropping systems, as shown in a 2010 study of farming systems across SSA and Asia.[25] For wheat in highland temperate systems of SSA, the authors find that major constraints limiting rice yield include the unavailability of quality seed, nitrogen fertilizer deficiency, and wheat rusts (fungal pathogens). For intensive rice and rice-wheat systems in South Asia, experts identified weed competition, nitrogen fertilizer deficiency, low soil fertility, and drought and intermittent water stress as primary constraints.

Farmers utilize a diverse mix of conventional and agroecological management practices to address these constraints and improve yields. The development and deployment of high-yielding crop varieties that are responsive to agronomic inputs has been critical to increasing potential yields. In some cases (such as U.S. maize), new cultivars are able to better withstand increased planting density, which allows for greater yield.[26] Given sufficient investment and ample water supplies, irrigation can be used to overcome chronic water stress. Further, installation of tile drainage systems can alleviate excessive moisture. Soil fertility constraints can be addressed through the use of both organic and inorganic fertilizers, appropriate crop rotations, mixed crop-livestock systems, and multi-cropping systems. In Brazil – and elsewhere in the tropics – acidic soils and aluminum toxicity are offset by additions of lime and phosphorus. Weeds, pests, and diseases can be addressed through a variety of practices as well. In the case of pests, biological control and integrated pest management can provide a chemical-free – but knowledge-intensive – alternative to pesticides. The economic feasibility and environmental impact of these various practices in different socioecological contexts will ultimately determine the contours of the policy landscape in which society attempts to close yield gaps.

Yield gaps are the cumulative result of decision-making by individual farmers who have weighed the perceived costs and benefits of changing their current agricultural practices and found the prospect either unattractive or unattainable. These decisions largely reflect the reasoned calculus of risk-averse, cash-constrained farmers who are either unwilling or unable to experiment with higher-yielding management techniques. Notwithstanding some evidence of irrational behavioral biases working against the purchase of fertilizer, such decisions are mostly consistent with economist T. W. Schultz's notion of the "poor but efficient" farmer.[27] Understanding the persistence of yield gaps thus requires attention to the incentives and constraints that under-yielding farmers face.

Market, policy, and sociopolitical failures all contribute to yield gaps by creating or exacerbating important differences in the costs and benefits of intensification for farmers in poorer countries relative to those in richer countries. Markets typically fail to provide poor, rural farmers adequate access to credit and insurance. In the absence of formal insurance, farmers may pursue a number of alternative strategies that often result in lower yields. These include: applying less fertilizer; forgoing the benefits of specialization and scale in order to reduce risk, as by planting a greater diversity of crops than would maximize yield alone; and shifting labor to nonfarm work in order to diversify income sources. Incomplete credit markets typically leave households unable to borrow at reasonable rates – if at all – inhibiting productive investments in livestock, irrigation pumps or seasonal fertilizer inputs that are critical for achieving higher yields. When households can neither insure against risk nor borrow in times of need, they are often forced to sell off productive assets. This coping strategy can lead to overinvestment in disposable assets, such as livestock, at the expense of higher-yielding alternatives, such as the purchase of more fertilizer, and can result in a cycle of declining yields over time.[28]

Whereas the governments of wealthy countries tend to lavish their relatively small agricultural sectors with subsidies of all kinds, poorer nations' governments have historically placed much of the tax and policy burden on their comparatively large and important agricultural sectors.[29] These perverse policies contribute to hyper-intensification in already high-yielding countries, while blunting the incentives to enhance productivity where yields are lowest. Such policies are often manifestations of underlying weaknesses in institutional quality, which give rise to other problems, including poorly established or minimally enforced property rights and an underprovision of public goods and services, such as agricultural research, extension programs, and transportation infrastructure. Insecure property rights make access to credit more difficult and heighten the risks of eviction, making investments in the land even less attractive.[30] Poor transportation infrastructure also inhibits the adoption of yield-improving technologies, particularly those requiring input intensification. Long, hazardous transport routes lead to higher fuel expenditures, and the loss of labor time and perishables in transit reduces the net prices that farmers receive. Farmers who face high costs of buying and selling in markets may choose to diversify their crop mix to satisfy their own demand for a variety of goods rather than investing in yield-increasing technologies for a smaller subset of crops.[31]

Were routine and pervasive market and policy failures not sufficient obstacles to yield improvement, farmers in many countries must also contend with episodes of civil and ethnic violence, and chronic political instability. These factors can disrupt supply chains, reduce demand, siphon human capital from the farm, deplete on-farm capital (including the quantity and variety of seed stocks), and generally heighten risks. Thus, they reduce the quantities of inputs and effort that farmers are willing and able to apply to the land. They may disproportionately affect the areas where additional inputs are needed most. The Rwandan civil conflict of the early 1990s provides the *ne plus ultra* example of such effects. Average yields (measured in terms of the per hectare caloric content of nutritional crops harvested) in the five-year period following the conflict fell by more than 20 percent relative to the five-year period preceding the conflict, with no evidence of a preexisting trend of decline.

Together, all of these factors – political, social, and economic – contribute to a poverty trap that is at once cause and consequence of under-yielding.

Breaking the cycle of poverty and low yields has the potential to enhance local and global food security and – ideally – reduce the environmental impact of agriculture. Food security is the state "when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life."[32] Closing yield gaps is not sufficient for ensuring food security (nor is it strictly necessary), but it can substantially improve a country's capacity to achieve this goal. If yield gaps are closed through improvements in technology or the elimination of market, policy, and social failures – rather than by an increase in inputs alone – farmers' production and income can expand even while greater supply drives down prices for urban households. The ripple effects of growth in the agricultural sector may augment urban food security not simply via the price mechanism, but by strengthening the economy and indirectly enhancing urban incomes.

Technological improvements may take a variety of forms, and strategies based on the adoption of high-yielding varieties and input intensification will have much different social and environmental consequences than strategies based on the adoption of agroecological technologies. Each strategy, in its ideal implementation, holds considerable promise for enhancing food security. Input-intensive technologies have the potential to vastly improve livelihoods and food security where transport infrastructure allows marketing of surplus production beyond the vicinity of the local community; credit and insurance markets are robust and accessible; and high-yielding varieties have been bred for local conditions. Alternatively, there exists potential to greatly reduce downside risk, promote diversity and self-sufficiency in food production, and even enhance expected yields and profits through the increasing adoption of agroecological principles. Adoption of these practices depends upon strong social networks among farmers that allow the transmission of best practices, and links between farmers, scientists, and civil society organizations.[33] These strategies need not be mutually exclusive, and there is considerable promise in the merging of best practices from both approaches.

The extent to which these best practices are adopted will likely determine the degree to which closing yield gaps leads to net benefits for local and global environmental quality. Concern is warranted, given that intensive management practices have led to soil degradation, widespread water pollution and nitrous oxide emissions from excess fertilizer application, use of toxic chemicals for pest and weed control, and overuse of water supplies.[34] Despite historic trends, promising evidence exists that yield gaps can be closed – and have closed, to some degree – in ways that minimize negative environmental consequences. University of Essex professor Jules Pretty and colleagues have documented the effects of 286 interventions to increase productivity in 57 developing countries.[35] While environmental outcomes were not explicitly documented, the authors focus on interventions that emphasized "resource-conserving" management practices: a broad description that includes integrated pest management, integrated nutrient management, conservation tillage, agroforestry, aquaculture, water harvesting, and livestock integration. The aggregate results are striking: these generally low-impact management changes led to an average yield increase of 80 percent for intervention participants. The greatest gains were possible for those farmers that started with the lowest current yields (achieving less than two tons per hectare), emphasizing the large increases in food supply possible from focusing on the most under-yielding areas.

Another encouraging example comes from agronomic trials aiming to improve the production and environmental performance of maize cultivation in China.[36] The study focused on nutrient management. This is a major problem in China, which experiences widespread pollution from agricultural fertilizers. In the trials, computer modeling and soil testing guided split doses of nitrogen throughout the growing season. Combined with balanced doses of phosphorus and potash, optimal planting dates, and appropriate planting density, the experimental trials were able to double maize yield while eliminating mass balance excess nitrogen. (The same amount of nitrogen was applied to the field and removed in the grain.) This study emphasizes the importance of the cropping system and the way inputs are utilized to realize more productive and environmentally friendly agricultural systems.

The availability and sustainability of water resources is also a major concern when considering yield gap closure. While irrigation is obviously an effective approach to ameliorating water stress, irrigation infrastructure can be expensive. Building such infrastructure requires either high energy or labor inputs and access to sufficient and – in the long run – sustainable water supplies. Rainwater harvesting is an alternative to ground- or surface-water-based irrigation schemes, and uses rainwater capture combined with irrigation to allow farmers to overcome intermittent dry spells. Conservation farming techniques that reduce soil evaporation (including no-till, mulching, intercropping, and windbreaks) can also preserve soil water for use by crops.[37]

Finally, we must also consider whether closing yield gaps will truly be able to spare land for nature, which is the major environmental benefit presumed to occur from yield gap closure. The rationale seems simple: given the massive growth in projected crop demand, achieving yield growth on existing lands will avoid biodiversity loss and carbon emissions from land clearing otherwise necessary to meet demand. However, the extent of the land-sparing effect is a topic of substantial debate.[38] Central to this debate is the degree to which yield-enhancing technology makes conversion of new lands to agriculture more profitable, even as it increases supply from existing land and leads to lower prices. The environmental benefits of sparing land will depend on where the "sparing" occurs relative to the intensification, and to what extent various intensive agricultural practices affect local biodiversity.

While full treatment of this complex issue merits its own article, historical trends provide strong evidence for the importance of the land-sparing mechanism. Even with constant patterns of per capita demand, an alternate world with no yield improvements after 1961 would have experienced a doubling of the cropland footprint and an additional two gigatonnes of carbon emissions per year.[39] As food demand continues to increase, we expect yield improvements and the closing of yield gaps to be necessary but not sufficient to spare land for nature. Enhanced governance and conservation efforts are also necessary.[40]

Recent research has put yield gaps on the map, both literally and figuratively. These efforts can inform and catalyze further inquiry into the causes of yield gaps and effective strategies for their closure that improve human well-being. More specific, we suggest that well-being can be advanced through food system changes that enhance food security and improve environmental quality. As the scientific literature on yield gaps continues to grow, research can contribute to these objectives by developing yield gap metrics that are increasingly nuanced in their accounting for local conditions, such as: the current health or fragility of agroecosystems; climate variability and projected climate change; assessments for locally important "orphan" crops; and the use of local crop varieties or landraces that may provide advantages other than – and possibly at the cost of – average yields. In doing so, yield gap research will become even more connected with agronomic and agroecological knowledge, and can inform the creation of more vibrant, productive, and biodiverse landscapes.

## ENDNOTES

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[1] Jonathan A. Foley, Navin Ramankutty, Kate A. Brauman, et al., "Solutions for a Cultivated Planet," *Nature* 478 (7369) (2011): 338; and David Tilman, Christian Balzer, Jason Hill, and Belinda L. Befort, "Global Food Demand and the Sustainable Intensification of Agriculture," *Proceedings of the National Academy of Sciences* 108 (50) (2011): 20260 – 20264.

[2] Tilman et al., "Global Food Demand and the Sustainable Intensification of Agriculture"; and David B. Lobell, Uris Lantz C. Baldos, and Thomas W. Hertel, "Climate Adaptation as Mitigation: The Case of Agricultural Investments," *Environmental Research Letters* 8 (1) (2013).

[3] David B. Lobell, Kenneth G. Cassman, and Christopher B. Field, "Crop Yield Gaps: Their Importance, Magnitudes, and Causes," *Annual Review of Environment and Resources* 34 (2009): 179 – 204.

[4] Foley et al., "Solutions for a Cultivated Planet," 338.

[5] Food and Agriculture Organization of the United Nations, *Global Forest Resources Assessment 2010* (Rome: Food and Agriculture Organization of the United Nations, 2010), http://www.fao.org/docrep/013/i1757e/i1757e.pdf; and Rodolfo Dirzo and Peter Raven, "Global State of Biodiversity and Loss," *Annual Review of Environment and Resources* 28 (2003): 137 – 167.

[6] Deepak K. Ray, Navin Ramankutty, Nathaniel D. Mueller, et al., "Recent Patterns of Crop Yield Growth and Stagnation," *Nature Communications* 3 (2012): 1293.

[7] Marena Lin and Peter Huybers, "Reckoning Wheat Yield Trends," *Environmental Research Letters* 7 (2) (2012): 1 – 6; and Patricio Grassini, Kent M. Eskridge, and Kenneth G. Cassman, "Distinguishing Between Yield Advances and Yield Plateaus in Historical Crop Production Trends," *Nature Communications* 4 (2013): 1 – 11.

[8] Emily S. Cassidy, Paul C. West, James S. Gerber, and Jonathan A. Foley, "Redefining Agricultural Yields: From Tonnes to People Nourished Per Hectare," *Environmental Research Letters* 8 (3) (2013): 1 – 8.

[9] Ray et al., "Recent Patterns of Crop Yield Growth and Stagnation."

[10] Foley et al., "Solutions for a Cultivated Planet."

[11] Tilman et al., "Global Food Demand and the Sustainable Intensification of Agriculture."

[12] Chad Monfreda, Navin Ramankutty, and Jonathan A. Foley, "Farming the Planet: 2. Geographic Distribution of Crop Areas, Yields, Physiological Types, and Net Primary Production in the Year 2000," *Global Biogeochemical Cycles* 22 (1) (2008): 1 – 19.

[13] Nathaniel D. Mueller, James S. Gerber, Matt Johnston, et al., "Closing Yield Gaps through Nutrient and Water Management," *Nature* 490 (7419) (2012): 254 – 257; Rachel Licker, Matt John-

ston, Jonathan A. Foley, et al., "Mind the Gap: How Do Climate and Agricultural Management Explain the 'Yield Gap' of Croplands around the World?" *Global Ecology and Biogeography* 19 (6) (2010): 769 – 782; and Kathleen Neumann, Peter H. Verburg, Elke Stehfest, and Christoph Müller, "The Yield Gap of Global Grain Production: A Spatial Analysis," *Agricultural Systems* 103 (5) (2010): 316 – 326.

[14] Lobell, Cassman, and Field, "Crop Yield Gaps: Their Importance, Magnitudes, and Causes."

[15] Mueller et al., "Closing Yield Gaps through Nutrient and Water Management."

[16] Ibid.

[17] Tony Fischer, Derek Byerlee, and Greg Edmeades, *Crop Yields and Global Food Security: Will Yield Increase Continue to Feed the World?* (Camberra: Australian Centre for International Agricultural Research, 2014), http://aciar.gov.au/files/mn-158/index.html.

[18] Liangzhi You, Stanley Wood, Ulrike Wood-Sichra, and Wenbin Wu, "Generating Global Crop Distribution Maps: From Census to Grid," *Agricultural Systems* 127 (2014): 1 – 9.

[19] Weston Anderson, Liangzhi You, Stanley Wood, Ulrike Wood-Sichra, and Wenbin Wu, "An Analysis of Methodological and Spatial Differences in Global Cropping Systems Models and Maps," *Global Ecology and Biogeography* 24 (2) (2014): 180 – 191.

[20] Ray et al., "Recent Patterns of Crop Yield Growth and Stagnation."

[21] Justin van Wart, K. Christian Kersebaum, Shaobing Peng, et al., "Estimating Crop Yield Potential at Regional to National Scales," *Field Crops Research* 143 (2013): 34 – 43.

[22] Lobell, Cassman, and Field, "Crop Yield Gaps: Their Importance, Magnitudes, and Causes."

[23] Martin K. van Ittersum, Kenneth G. Cassman, Patricio Grassini, et al., "Yield Gap Analysis with Local to Global Relevance – A Review," *Field Crops Research* 143 (2013).

[24] Tilman et al., "Global Food Demand and the Sustainable Intensification of Agriculture"; Mueller et al., "Closing Yield Gaps through Nutrient and Water Management"; and Neumann et al., "The Yield Gap of Global Grain Production: A Spatial Analysis."

[25] Stephen R. Waddington, Xiaoyun Li, John Dixon, et al., "Getting the Focus Right: Production Constraints for Six Major Food Crops in Asian and African Farming Systems," *Food Security* 2 (1) (2010): 27 – 48.

[26] R. A. Fischer and Gregory O. Edmeades, "Breeding and Cereal Yield Progress," *Crop Science* 50 (S1) (2010): S85 – S98.

[27] Esther Duflo, "Poor but rational?" in *Understanding Poverty*, ed. Abhijit Vinayak Banerjee, Roland Bénabou, and Dilip Mookherjee (New York: Oxford University Press, 2006), 367 – 378; Esther Duflo, Michael Kremer, and Jonathan Robinson, "Nudging Farmers to Use Fertilizer: Theory and Experimental Evidence from Kenya," *American Economic Review* 101 (6) (2011): 2350 – 2390; and Theodore William Schultz, *Transforming Traditional Agriculture,* Studies in Comparative Economics, No. 3 (New Haven, Conn.: Yale University Press, 1964).

[28] Mark R. Rosenzweig and Kenneth I. Wolpin, "Credit Market Constraints, Consumption Smoothing, and the Accumulation of Durable Production Assets in Low-Income Countries: Investments in Bullocks in India," *Journal of Political Economy* (101) (2) (1993): 223 – 244.

[29] Peter H. Lindert, "Historical Patterns of Agricultural Policy," in *Agriculture and the State: Growth, Employment, and Poverty in Developing Countries (Food Systems and Agrarian Change)*, ed. C. Peter Timmer (Ithaca, N.Y.: Cornell University Press, 1991), 29 – 83.

[30] Gershon Feder, Tongroj Onchan, Yongyuth Chalamwong, and Chira Hongladarom, *Land Policies and Farm Productivity in Thailand* (Baltimore: Johns Hopkins University Press, for the World Bank, 1988).

[31] Steve Were Omamo, "Transport Costs and Smallholder Cropping Choices: An Application to Siaya District, Kenya," *American Journal of Agricultural Economics* 80 (1) (1998): 116 – 123.

[32] Food and Agriculture Organization of the United Nations, *The State of Food Insecurity in the World 2015* (Rome : Food and Agriculture Organization of the United Nations, 2015), http://www.fao.org/hunger/en/.

[33] Miguel A. Altieri, "Agroecology : The Science of Natural Resource Management for Poor Farmers in Marginal Environments," *Agriculture, Ecosystems and Environment* 93 (1 – 3) (2002) : 1 – 24.

[34] P. A. Matson, W. J. Parton, A. G. Power, and M. J. Swift, "Agricultural Intensification and Ecosystem Properties," *Science* 277 (5325) (1997) : 504 – 509 ; and David Tilman, Kenneth G. Cassman, Pamela A. Matson, et al., "Agricultural Sustainability and Intensive Production Practices," *Nature* 418 (6898) (2002) : 671 – 677.

[35] Jules N. Pretty, Andrew D. Noble, Deborah Ann Bossio, et al., "Resource-Conserving Agriculture Increases Yields in Developing Countries," *Environmental Science and Technology* 40 (4) (2006) : 1114 – 1119.

[36] Xin-Ping Chen, Zhen-Ling Cui, Peter M. Vitousek, et al., "Integrated Soil-Crop System Management for Food Security," *Proceedings of the National Academy of Sciences* 108 (16) (2011) : 6399 – 6404.

[37] Johan Rockström, "Water for Food and Nature in Drought-Prone Tropics : Vapour Shift in Rain-Fed Agriculture," *Philosophical Transactions of the Royal Society B* 358 (1440) (2003) : 1997 – 2009.

[38] Lobell, Baldos, and Hertel, "Climate Adaptation as Mitigation."

[39] Jennifer A. Burney, Steven J. Davis, and David B. Lobell, "Greenhouse Gas Mitigation by Agricultural Intensification," *Proceedings of the National Academy of Sciences* 107 (206) (2010) : 1 – 6.

[40] William F. Laurance, Jeffrey Sayer, and Kenneth G. Cassman, "Agricultural Expansion and Its Impacts on Tropical Nature," *Trends in Ecology and Evolution* 29 (2) (2014) : 107 – 116.