Diffusion of modern crop varieties associated with 20th century infant mortality declines

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There is considerable debate on the potential for modern staple seed varieties (MVs) to advance nutrition, and little is known about the contribution of MV diffusion during the "Green Revolution" to the global reduction in mortality achieved during the 20th century. Here we provide global scale estimates of the relationship between MV diffusion and infant mortality between 1960–2000 by constructing a novel, spatially-precise indicator of MV diffusion and leveraging child-level data from nearly 600,000 children across 18,138 villages in 36 developing countries. Results indicate that the diffusion of MVs reduced infant mortality by 3.7–4.2 percentage points (from a baseline of 17%), with stronger associations for male infants. These results are robust to a host of

statistical controls and alternative measures of MV diffusion that reduce potential confounding. The sizable contribution of MV adoption to improved welfare should inform global food and development policy.

Modern crop varieties (MVs), developed by dozens of national agriculture programs with the support of international agricultural research centers, spread globally during the past 70 years in one of the most far-reaching technological revolutions of modern time. While there is little disagreement that the use of MVs played a large part in the 20^{th} century's dramatic increase in staple crop production (*1*), much less is known about the relationship between MV adoption and household health and welfare (*2*). How agricultural productivity translates into improved nutrition and health remains imperfectly understood and a topic of intense current research, as are the drivers of mortality declines in the developing world during the course of the 20^{th} century (*3*).

An improved understanding of these linkages can have important implications for current policy debates on the merit of continued investments in staple crop improvements. Although rising crop yields throughout the Green Revolution increased global food production and may have helped avoid cropland extensification (*4–6*), many scholars have emphasized the negative impacts of the Green Revolution on dietary diversity and a range of environmental outcomes that influence human welfare, arguing that strategic re-evaluation of R&D priorities for agriculture is warranted (*7–12*). Meanwhile, there is a steady decline in funding for cereal crop improvement over the last few decades in sub-Saharan Africa, the continent with least diffusion of MVs (*13, 14*). Improved estimates of the welfare impacts of MV adoption can help to more accurately weigh benefits and drawbacks of agricultural technologies, as well as to inform the recent debate about whether investing in increased smallholder agricultural productivity is an effective strategy for economic development, health improvement, and poverty alleviation in sub-Saharan Africa (*11, 15, 16*).

There are multiple potential pathways through which increases in yields can improve human health and welfare (*1*). For food insecure subsistence farmers, higher yields directly lead to increased caloric consumption. For farmers who are net food sellers, income may also increase with yield, depending on how far prices decline as total production increases. Lower food prices allow the non-farming population to improve food intake and consume more of other (potentially health-enhancing) products.[1] Yield increases might also have triggered broader structural transformation in the economy leading to urbanization, higher productivity, a larger tax base and subsequent public health investments (*23–25*). Some researchers have cited Africa's relative lack of a green revolution as a key reason why the region has not yet experienced greater long-term economic success (*26, 27*). Despite these myriad possible channels of influence, evidence-based assessments of the historical association between the diffusion of MVs and human welfare on a global scale remain remarkably scarce.

This paper investigates the association between MVs and human health at a precision and scale that has not been attempted to date, using spatially precise household level data on the mortality of children born between 1961 and 2000 in 36 developing countries from the Demographic and Health Surveys[2]. The analysis focuses on a powerful summary indicator of health and welfare: infant mortality (IM). IM is highly correlated with income and other welfare indicators both across and within countries, as well as over time, and is widely used to assess levels of economic development (*29–31*). IM has declined dramatically over our study period: from 154 deaths per 1,000 live births in 1960 to 42 deaths in 2010 (*32*). While much of this decrease is undoubtedly driven by improvements in public health provision, it is also necessary to understand whether the diffusion of MVs and subsequent agricultural productivity improvements

[1]The vulnerability of rural households to food shortages is evident in the effect of large-scale feeding programs on anthropometric outcomes (*17*), and in how weather shocks affect their children's height, weight, and school completion as adults (*18, 19*). Agricultural technology improvements are associated to reductions in the likelihood of households living below the poverty line in Mexico (*20*), Ethiopia (*21*), Rwanda and Uganda (*22*).

[2]For details about Demographic and Health Surveys, see http://www.measuredhs.com

also contributed to health gains.

Over the same period, MVs diffused extensively across the developing world. This occurred in stages, largely dictated by technological advances at the international agricultural research centers (IARCs) for different crops and different agroecological zones. Early successes in the 1960s benefitted wheat and rice varieties, in part because technologies available for these crops in developed countries could be easily transferred. Breeding programs for many other crops had no such earlier science to rely on, contributing to why crops such as sorghum and millet had modern varieties first available significantly later (in the 1980s). International research programs led to improved varieties, which were then localized by national agricultural research centers. The arrival of MVs at a given location and time, therefore, was determined to an important extent by the scientific advances in the IARCs, the location's agroecological suitability for different crops, and how much additional breeding would have to be done by national agriculture research centers (*1*).

Reconstructing modern variety diffusion

A straightforward approach to studying the role of MVs in the decline of IM on a global scale would consist of examining correlations at the country-level. However, an inspection of these correlations does not yield conclusive results (Table S1). This is perhaps not surprising given the sample size and limitations of using country level summaries of variables that display substantial sub-national heterogeneity. Moreover, even if a significant correlation were found through such an analysis, it would be difficult to interpret, because it could spuriously arise through unobservable confounding variables driving economic growth (*33*). For example, countries experiencing faster economic growth in non-agricultural sectors might be better placed to invest in both agriculture (perhaps through subsidizing MVs) and public health.

Examining the association at a sub-national level would help address many of these challenges, but is severely impeded by lack of global scale data on subnational diffusion of MVs. To overcome this data gap, we construct high resolution, sub-national proxies of MV diffusion and couple them to geo-referenced household-level IM indicators from publicly available household survey data. The MV Diffusion Indicator (MVDI) is constructed by combining high-resolution global crop maps with country-level data on MV diffusion over time. Variation in this indicator therefore combines fine spatial variation in cropping patterns with crop-specific temporal variation in the diffusion of MVs, which partly results from differences across crops in international agricultural research priorities and breakthroughs during the course of the Green Revolution. To ensure robustness of results, we develop and analyze three variants of the MVDI based on three distinct global crop map datasets (*34–36*).

To illustrate the approach using one country as an example, Figure 1 shows the construction of MVDI in the case of Nigeria, using the EarthStat 2000 crop map data (*34*). The figure displays the spatial distribution (top) and national-level MV diffusion (middle, data from (*37*)) for each of six crops (out of the eleven in EarthStat 2000). These are combined to generate a gridded map (bottom) of the diffusion of MVs in each year, weighted across all crops (see supporting material). For example, MVs for millet diffused late because IARCs did not produce varieties until the 1980s (*1*). Since millet happens to be a dominant crop in much of the northern part of the country, this leads to a relatively low rate of overall MV diffusion in those regions.

The method used to construct the MVDI builds on a well-known empirical approach known as a Bartik (or shift-share) instrument (*38*). That is, it uses a measure of change over time at the aggregate level (national MV adoption, partly reflecting breakthroughs in international agriculture research), and considers how much different clusters were exposed to change, given their relevant characteristics (initial crop mix). The MVDI provides a good predictor of historical localized MV diffusion and is highly correlated to actual MV diffusion where such data are available (Table S2).

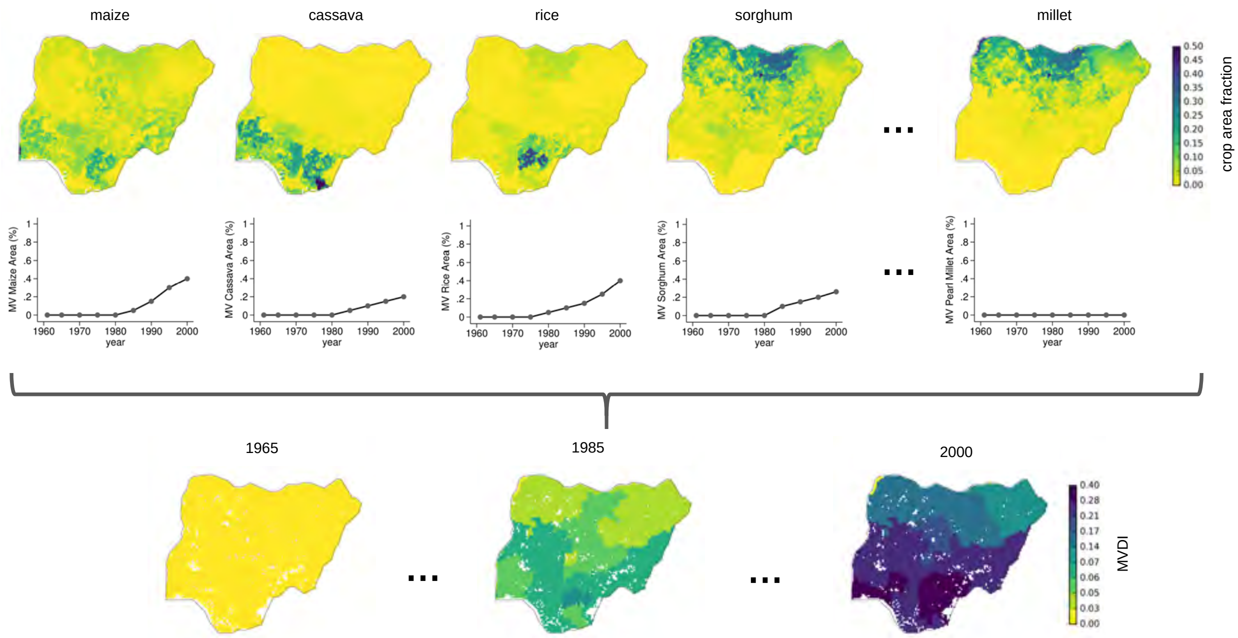

Figure 1: Construction of a global, cluster-year level predictor of modern crop variety (MV) diffusion (as percent of cultivated land). In each cluster, country-level crop specific MV diffusion data (*1*) is averaged using the local cluster crop mix, obtained from global, spatially precise crop map datasets.

IM data is collected from Demographic and Health Surveys (DHS) in all 36 developing countries where the data is geo-referenced, and in our sample includes more than 600,000 child observations. Mean IM for each of the 18,138 DHS sampling clusters in our data (each cluster usually encompasses a village or a small group of villages) is shown in Figure 2. Using the georeferenced DHS data (as opposed to DHS surveys geolocated only to a district or other larger administrative unit) is important because of significant spatial variation in both IM and crop mix (evident in Figures 1 & 2), and because exploiting the rich subnational variation is key to explaining most spatial variation in child mortality across sub-Saharan Africa (*28*).

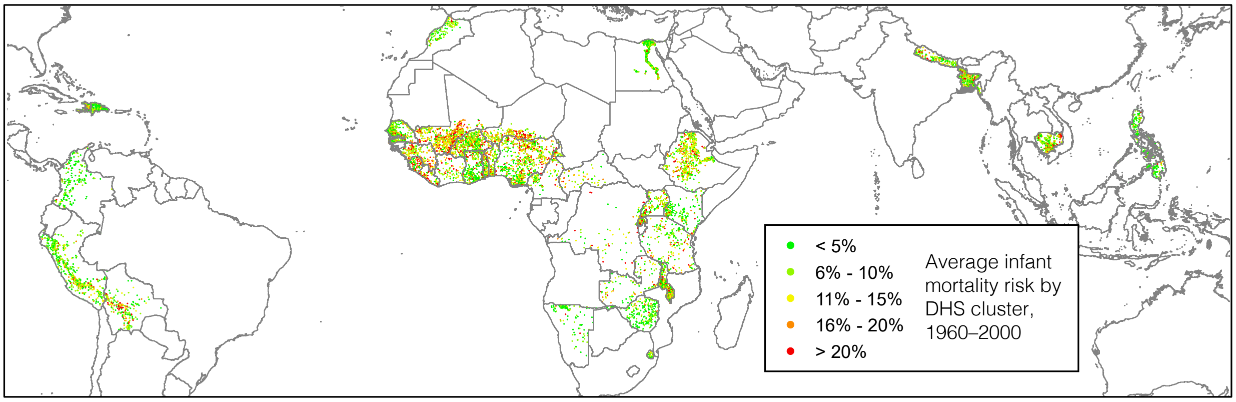

Figure 2: Mean infant mortality (IM) risk. IM is averaged across children in each sampling cluster of the Demographic and Health Survey data in 36 developing countries, spanning 1960–2000 ($N = 18,138$ villages).

Statistical approach

Our statistical analysis compares trends in MV diffusion and IM declines across different locations in the same country in a cluster-level difference-in-difference approach. By comparing changes in MV and IM, rather than their absolute levels, we avoid basing our estimates on cross sectional comparisons across locations, which are highly susceptible to bias from confounding variables (for instance, climatic and geographic factors). By only comparing deviations from flexible national trends (that is, by including country-by-year fixed effects), we implicitly control for all country-level, time variant variables (economic growth, agricultural policy changes or vaccination campaigns, for example) that might have otherwise biased country-level analyses of the MV-IM relationship. Our analysis therefore asks whether the change in MV adoption in a given DHS cluster was ahead of or behind the national trend, and whether this deviation in the rate of change was associated with a deviation in IM decline.

Basing our estimates only on sub-national deviations from trends (and pooling across countries) offers a significant improvement on cross-country analyses. It dramatically increases sample sizes and data resolution, allowing for more precise statistical estimations and allowing implicit and explicit controls for numerous other potential drivers of IM declines. While our approach does not eliminate all possible causes of potential bias, it greatly reduces the scope for such bias when compared with all existing studies on a global scale. Furthermore, we subject our results to a wide range of robustness tests and alternative regression models (see Supporting Information), which include controlling for indicators of other drivers of IM decline such as maternal education levels or access to public health, controlling for predictors of localized economic growth, removing crop-specific trends that could potentially be driving the association, and limiting the comparison to siblings. Finally, to eliminate another class of potential confounders, we test a variant of our model in which each country's MVDI is constructed by using not that country's own MV diffusion rates, but the average rates of its neighboring countries. By construction, this version of the MVDI cannot be confounded by patterns of economic development within a country that could, theoretically, generate a spurious correlation with local rates of IM declines. Since random assignment of MV diffusion across populations is only feasible at local scales, we believe our approach offers the most rigorous feasible quasi-expermental alternative to the study of this enormously important question on a global scale.

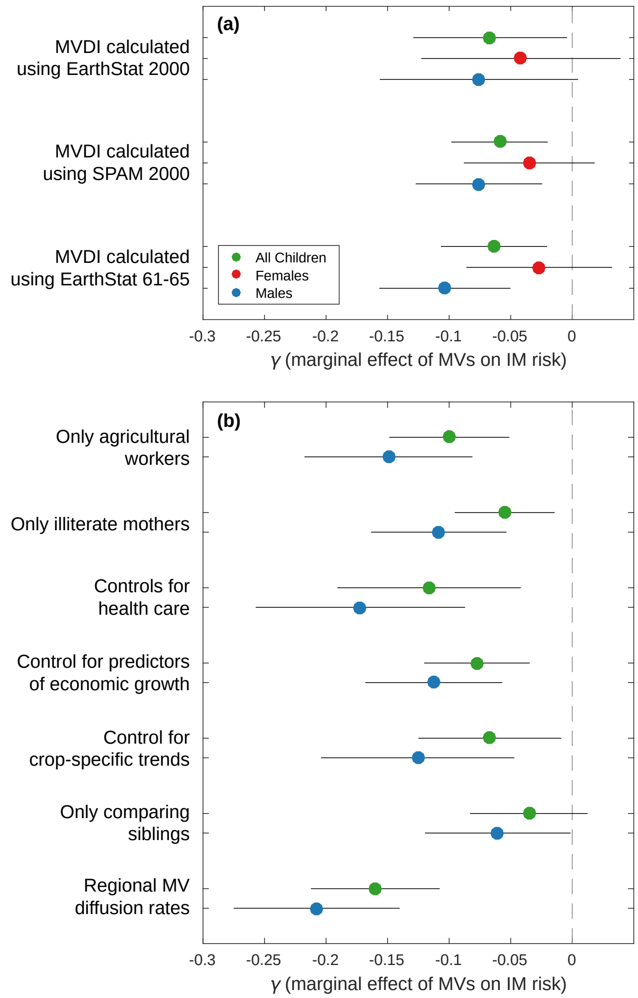

Figure 3: Estimated impact of modern varieties on infant mortality. Each estimate represents γ from the following estimating equation: $y_{ivct} = \gamma MVDI_{vct} + u_v + Z_{ct} + X_{ivct} + e_{ivct}$ where y_{ivct} is a binary indicator of infant mortality (death in the first year of life), i.e. child *i* in village *v* in country *c* died in its birth year *t*; u_v are village fixed effects and Z_{ct} are country-by-year FE; X_{ivct} includes quadratic in mother's age (at birth of child) and sex of child; and e_{ivct} are idiosyncratic errors clustered at subnational (admin) level. 95% confidence intervals shown. The sample is restricted to rural villages and mothers who report to have never migrated. Panel (a) shows estimates using three different crop maps to construct MVDI and reports estimates by child sex for each crop map. Panel (b) reports estimates for both sexes and for males from the following variants on the model: limiting the sample to mothers that report being agricultural wage laborers; limiting to mothers who are illiterate; controlling for mother's antenatal care visits, duration of breastfeeding, and child vaccination; detrending the data as a function of distance to coast; detrending the data according to crop mix; only comparing siblings by adding mother fixed effects; and constructing the MVDI using neighboring countries' MV diffusion instead of the country itself. See Supporting Information for details on all results.

Modern crop varieties and infant mortality

Relative to the national trend, children born when MVs achieved greater diffusion in their area were less likely to die in infancy (Figure 3a, see Table S3 for details). The top estimates in Figure 3a use the MVDI constructed with the EarthStat global crop maps for 11 crops in 2000 (*34*). The magnitude of the estimates suggests that an increase in MV diffusion from no MV to full MV coverage is associated with a 7 percentage point decline in infant mortality, and that an increase of one standard deviation (12%) in MV diffusion is associated with a 0.8 percentage point decline in infant mortality. For context, the sample mean of IM is 10%. Analogous estimates derived using the SPAM and historical (1961-65) EarthStat global crop datasets are very similar in both magnitude and statistical significance, indicating results are not sensitive to choice of crop dataset. Results are statistically unchanged if we add India, a country central to the history of the Green Revolution that does not have DHS data georeferenced to the village level (Table S4). Region-specific estimates reveal that the negative association between MV diffusion and IM holds independently across regions in which sufficient variation in crop mix exists (Table S5).

We also report impacts separately by the child's sex, for two reasons. First, male infants consistently exhibit higher mortality rates than females, especially in response to in-utero stress (*39*). Many scholars attribute the difference to males being biologically weaker (*40–42*) and more susceptible to disease than female infants due to a more vigorous immune response among females (*43–45*), though the size of the biological effect is contested (*46*). Second, evidence from several studies indicates that households often prioritize male over female children in difficult times (*18, 19, 29, 47*), including in terms of nutrient allocation (*48*).

Figure 3a shows that across all three crop datasets, female IM displays a negative association with MVDI that is smaller in magnitude than the pooled effect across sexes and is statistically insignificant. Male IM, on the other hand, displays a larger and highly significant association.

Coefficient estimates imply that males born when MV diffusion in their cluster is one standard deviation higher (12%) benefit from a 0.9–1.2 percentage point reduction in IM risk (as compared to an average IM of 11% across the entire sample of males). These results suggest that if MV diffusion does in fact improve infant health, whether through increased caloric intake or higher incomes, the effect is greater among male than female infants.

To test whether the sex-differentiated salubrious effects of MVs occur in utero, we estimate the impacts of MVDI on the infant male-to-female sex ratio of the children in the sample (i.e. live births), but do not find consistent evidence of such an impact (Table S6). This suggests that the effects of MVs on IM, in particular those evident among males, do not occur by changing the rate of miscarriage. Controlling for sex-specific birth order, which amounts to comparison of children of the same sex and parity, does not alter the pattern of the results.

Figure 3b shows that extended tests using the 1961-1965 EarthStat dataset result in consistent estimates in relevant sub-populations and across different sets of controls. The beneficial effects of MV diffusion are stronger among poorer households (Table S7) and in areas farther from cities (Table S8). Results are robust to a range of alternative models that include controlling for access to public health and education (Table S9), flexibly controlling for unobserved sources of economic growth by crop patterns or by access to trade (Table S10), adding migrants to the sample (Table S11), and only comparing children of the same birth order or only comparing siblings (Table S12). We also find MV diffusion is associated with reductions in adverse child growth outcomes (Table S13), although the sample size for anthropometric analysis is much smaller. Placebo tests conducted by using only the urban sample yield null results (Table S14), raising confidence in the validity of the model and results.

The final two tests in Figure 3b provide the strongest pieces of evidence for a causal impact of MVs on IM. The first is to limit the comparison to siblings who are exposed to different levels of MV diffusion at birth, thus eliminating any confounding variable at the family level that is unchanged between the births of the two children (Table S12). Even with this specification that severely limits statistical power, we find consistent and statistically significant results for male infants. The estimate for all children, while not significantly different from zero, is statistically indistinguishable from our main result. A second test guards against confounding variables correlated both to a country's adoption of MVs and health improvements by constructing an alternative MVDI using the average MV diffusion in the country's region, while excluding the value for the country itself. Our results using these alternative (plausibly exogenous) MV diffusion rates are slightly larger in magnitude than the main results, strengthening the case for a causal interpretation (Table S15).

Global health impacts of MV diffusion

In the year 2000, around 114 million children were born per year in the developing world (*49*), while 63% of crops were planted to MVs. Our estimates suggest that this level of MV diffusion reduced the infant mortality rate by 3.7–4.2 percentage points (from a baseline of 17% around 1960), which translates into around 4.5 million infant deaths averted per year by the year 2000.

It is important to note that the diffusion of MVs was often accompanied by increases in other agronomic inputs such as fertilizers, irrigation, and pest control (*8*). Our estimate of the effect of MV diffusion implicitly includes the yield-enhancing effects of input intensification that occurred simultaneously with the use of MVs. Therefore, the estimated effects on health to some degree reflect not only the effect of the MVs themselves, but of the wholesale adoption of more intensive and productive cropping practices, where they went hand in hand with the use of MVs. A second point is that our indicator tracks replacement of traditional crop varieties with modern varieties. Additional crop yield and human welfare benefits would be expected as more advanced modern varieties replace earlier MVs, but our approach only measures the average health impact across all types of modern varieties that were adopted.

While recent discussions of malnutrition rightly emphasize the importance of micronutrient supplementation and production (*7*), our estimates provide compelling evidence that the health benefits of broad-based increases in agricultural yields should not be overlooked. Our results indicate that the health effects of MV diffusion differed substantially based on the sex of the infant, consistent with other evidence of sex-specific effects of income shocks on children (*18,19*). This gender disparity could reflect both socio-economic and biological factors. One possibility is that parental discrimination in resource allocation is driving the results. Alternatively, infant males may benefit disproportionally from higher maternal and infant caloric intake due to biological characteristics that contribute to underlying differences in IM rates between the sexes. Identifying which of these mechanisms is at work remains an important avenue for future research.

Our empirical strategy does not allow us to directly identify the mechanism through which MV diffusion decreases IM, although the primary candidate mechanisms include an increase in food consumption by mothers in subsistence households, an increase in income by farming households, and a decrease in food prices overall. Since our estimates are based on differences in the rates of IM declines across villages in the same country, they can only capture those impacts of MV diffusion that are localized in nature. For example, the impacts of uniform declines in food prices across an entire country would be “missed” by our analysis. Only localized relative changes in income and food prices would be captured, meaning our analysis may under-estimate the true impact. We note, however, that imperfect market linkages in developing countries make spatially localized effects on prices quite likely (*50–52*).

The aggressive suite of statistical controls and robustess checks in our analysis dramatically reduces the assumptions required to interpret the association between changes in MV and IM in a causal manner. While there are numerous other factors that can affect IM, our results are robust to controlling for observable factors, and the construction of our MV proxy makes it unlikely that it will be systematically correlated with unobservable ones (see the Supporting Information for details). Moreover, results from constructing MVDI using neighboring countries' MV data further strengthens the argument that our estimates measure the causal impact of MV diffusion whose timing is largely driven by international research investments.

Since decreases in mortality likely imply improvements in nonfatal health conditions, our results provide striking evidence for the health benefits of agricultural productivity growth. They suggest that continued investments in agricultural research and development as well as diffusion of existing MV varieties may lead to substantial human welfare benefits in areas where MV diffusion (*1, 53*), input intensity (*54, 55*), and crop productivity (*54, 56, 57*) remain low. Targeting efforts using new geospatial estimates of malnutrition prevalence (*58*) may provide an even larger impact. Further agricultural research will also be needed to minimize the potentially adverse effects of productivity increases on local environments and dietary diversity. These insights will be a key part of meeting the Sustainable Development Goal targets of ending hunger and doubling agricultural productivity and incomes of small-scale food producers by 2030.

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