Agricultural Productivity and Income Divergence: Evidence from the Green Revolution

Huang, Kaixing

17 May 2020

Agricultural Productivity and Income Divergence: Evidence from the Green Revolution

Kaixing Huang
China Center for Agricultural Policy, Peking University

Developing countries sharing nearly identical growth trends for centuries dramatically diverged in terms of income per capita over the last half-century. Using data from 78 developing countries, this study shows that the Green Revolution (GR) since the 1960s can explain most of the income divergence. Beyond the understanding that agriculture growth promotes economic growth, the study shows that developing countries less suitable for cultivating GR crops were substantially damaged by GR-induced grain imports, which increased fertility and retarded human and physical capital formation. A counterfactual analysis removing GR's effect showed parallel growth trends similar to that prior to the GR.

Keywords: The Green Revolution, international trade, income divergence
JEL O47, O13, N50

1. Introduction

The dramatic transformation in the distribution of income across the globe in the past two centuries is one of the most significant mysteries. As presented in Figure 1, the two major phases of income divergence in modern history coincided with the two agricultural revolutions in terms of both timing and region. Starting around the early 19th century, Western countries diverged gradually from the rest of the world, closely following the British Agricultural Revolution, which took place most remarkably in 18th century England and then spread first to Europe and Western offshoots (Overton 1996, Allen 2011).[1] The figure also classifies countries that have been lagging since the first income divergence into two groups based on their 2000 adoption rate of high-yielding crop varieties (HYVs), which characterized the Green Revolution (GR) in the developing world since the 1960s (Pingali 2012). It shows that after sharing virtually identical growth trends for centuries, countries with high HYV adoption suddenly took off and diverged from the rest of the developing world since the GR. These coincidences naturally lead to the conjecture that the agricultural revolution is a major cause of the global income divergence.

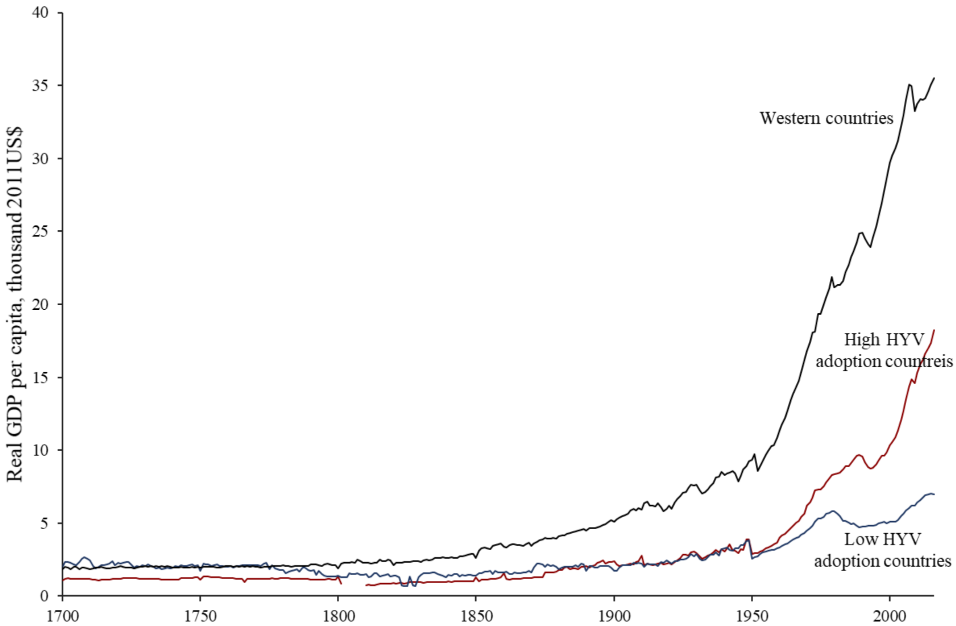

Figure 1. Two phases of income divergence in modern history

Notes: This figure classifies 134 countries with a population of more than 1 million in 1960 into three groups: 30 developed countries from the Western world (including most European countries, Western offshoots, and Japan; excluding Eastern European and South American countries), 66 developing countries with the 2000 adoption rate of high-yielding crop varieties (HYVs) below the developing world average (i.e., the low HYV adoption countries, see Section 4.2 for details), and the remaining 38 countries (i.e., the high HYV adoption countries). The data on GDP per capita (in thousand 2011US$) are derived from the Maddison Project Database 2018.

[1] The first income divergence in Figure 1 is usually referred to as the Great Divergence or European miracle (Jones 1981, Pomeranz 2000).

However, the importance of the agricultural revolution for historical income divergence has not been quantified, although there exists abundant evidence suggesting positive causal links from agricultural growth to economic development.[2] Existing studies mainly explain the first income divergence (i.e., the Great Divergence) by non-agricultural factors such as geographical and institutional factors, human capital formation, ethnicity, colonialism, and globalization.[3] The second income divergence is generally recognized as the "conditional convergence" between the developing and developed world (Ben-David 1993, Acemoglu 2009), instead of the income divergence among developing countries highlighted in this study. The conditional convergence, instead of the unconditional convergence predicted by workhorse growth models, is usually explained by cross-country differences in saving rates, fertility rates, human capital, institutional quality, colonial history, and geographical features (Barro and Sala-i-Martin 2004).

This study attempts to quantify the causal effect of the agricultural revolution on cross-country income divergence using data from the GR.[4] The GR has remarkably increased grain productivity in the developing world; however, the productivity gains have been significantly uneven across developing countries (Evenson 2005). By examining the GR's effect on country-level GDP per capita, this study attempts to answer the following questions: To what extent could the asymmetric effect of the GR across developing countries explain the second income divergence? What are the mechanisms behind the effect? Has the growth of countries benefited more from the GR adversely affecting the growth of countries that gained less agricultural productivity from the GR? Why does the second income divergence occur so much more

[2] Important recent studies on the positive causal links include, for example, Nunn and Qian (2011), Kopsidis and Wolf (2012), Andersen et al. (2016), Chen and Kung (2016), Bustos et al. (2016), Dall Schmidt et al. (2018), Gollin et al. (2018), and Carillo (2021).

[3] For example, Mokyr (2001) and Acemoglu et al. (2005) argued that institutions that facilitated the protection of property rights and the diffusion of knowledge have been the prime factors that enabled the earlier European take-off and the subsequent divergence across the globe; Jones (1981) and Pomeranz (2000) emphasized the effect of geographical factors on economic growth and the Great Divergence; and Galor and Weil (2000) and Galor and Mountford (2006) highlighted the role of human capital in the Great Divergence.

[4] Verifying the causal link from the British Agricultural Revolution to the first income divergence has been difficult because both events occurred gradually and lasted for centuries (Mokyr 2011, Jones 2016). It is almost not possible to exclude the possibility that it might be the high food demand and improved technology from the emerged European countries that caused the British Agricultural Revolution. Another important difficulty is the lack of cross-country comparable agricultural data for most countries during the 19th century.

dramatically?[5]

There are two facts that are critical for understanding the impact of the GR on income divergence. First, agricultural productivity gained from the GR differed substantially across developing countries with different suitability for cultivating GR crops (i.e., HYVs). Second, developing countries less suitable for cultivating HYVs experienced dramatic increases in grain imports following the GR (see Figure 2). Based on these facts, I developed a simple model to understand the impact of the GR. The model assumes two otherwise identical *open* countries, one is suitable for cultivating the HYVs (GR-advantaged) while the other is *not* (GR-disadvantaged). Each country contains three sectors: mining, agriculture, and manufacturing; agriculture and manufacturing produce consumption goods, while mining produces raw materials for manufacturing. The model depends on three assumptions to draw implications: (i) learning-by-doing is the driving force of economic growth, and manufacturing has the highest potential of learning; (ii) human capital is a necessary input in production, and higher returns to human capital reduce fertility and increase education; and (iii) Engel's law is embodied in the utility function and thus the demand shifts from food to manufactures as per capita agriculture output growth.

For the GR-advantaged country, the model predicts that higher agricultural growth from the GR reduces food prices, shifts labor to non-agricultural sectors, increases the production in manufacturers, enhances the manufacturing productivity (through learning-by-doing), raises returns to human capital, reduces fertility, increases education, reduces manufacturing prices, and increases raw material prices. The GR has no direct effect on the country unsuitable for cultivating HYVs but causes it to increase imports of food and manufactures and to increase the exports of raw materials by altering international prices. For the GR-disadvantaged country, the GR-induced trade shifts production from agriculture and manufacturing to mining, reduces learning and thus productivity growth in manufacturing, reduces returns to human capital, increases fertility, and reduces education. The opposite effect of the GR on growth determinants in countries suitable and unsuitable for cultivating HYVs leads to the income divergence between them.

[5] As presented in Figure 1, it took more than two centuries for the income ratio between the currently developed and less-developed countries to increase from 1.3 in 1800 to 3.0 in 2016; however, it took only half a century for the income ratio between the two groups of less-developed countries to increase from 1.2 in 1960 to 2.6 in 2016.

The model suggests two channels for the GR to affect income: the direct effect via domestic HYV adoption, and the indirect effect via international trade. Although the direct effect is expected to benefit all countries adopting HYVs, the indirect effect is expected to only benefit countries with high HYV adoption and to damage countries with low HYV adoption. The direct effect has been rigorously estimated by Gollin et al. (2018). Therefore, the main work of this study is to estimate the indirect effect and then combine it with the direct effect to evaluate the GR's total effect on cross-country income divergence. This study estimates the indirect effect in two steps: first, it estimates the effect of the GR on grain trade; second, it estimates the effect of the GR-caused grain trade on income per capita.[6]

The estimations are based on 78 developing countries, whose data on the adoption rate of HYVs are available for the period of 1960 to 2000 from Evenson and Gollin (2003b).[7] Using the HYV data, I constructed a measure of the GR's differential effect on grain productivity across countries: the relative *disadvantage* in adopting HYVs (RDS), which is calculated as the developing-world harvesting-area-weighted average adoption rate of HYVs minus the individual country HYV adoption rate. According to the construction, a country with a higher RDS is more disadvantaged during the GR. I then estimate the effect of the GR on grain trade by regressing the log net grain imports on the RDS in a fixed-effect panel model. The estimation showed that a one-unit increase in the RDS raises the net grain imports by 8 percentage points. To address the concern that the RDS could be endogenous, I also constructed the *predicted* RDS based on the country-level agro-climatic suitability for cultivating HYVs (instead of the actual HYV adoption rate). A virtually identical effect was estimated when using the predicted RDS as the instrument variable (IV) for the RDS in the estimation.

I then move on to estimate the effect of grain imports on income by regressing the log GDP per capita on the log net grain imports in a fixed-effect panel model that uses

[6] Note that, as will be detailed later, the main estimation uses grain trade (but not the trade of other products) as the intensity measure of the effect of GR via trade. This is primarily because the GR directly affects cross-country relative grain productivity (and thus grain trade), but it only indirectly affects the relative productivity of other products through affecting grain productivity. As such, using grain trade as the intensity measure could capture the GR's effect through the trade of other products. Appendix C3 estimates the effect by using the trade of manufactures and raw materials as the intensity measures. All estimates indicate that the GR-induced trade significantly reduces income per capita in the GR-disadvantaged countries, irrespective of the trade measure used.

[7] The 78 countries accounted for approximately 90 of the developing world population in 1960, according to the Maddison Project Database 2018. The study sample will be extended to 118 countries and up to the year of 2016 for robustness checks.

the (predicted) RDS as the IV for grain imports. The estimation showed that a 1 percentage point increase in net grain imports reduces GDP per capita by 0.14 percentage points. Combining this estimate with the estimated effect of the GR on grain imports, I found that for an average GR-disadvantaged country (where the RDS>0), the GR-caused grain imports reduced its GDP per capita by 42 percentage points (of the 1960 GDP per capita) by 2000. The estimated effects are comparable when including various control variables, using alternative IVs, measuring grain imports by the import-consumption ratio, or employing a standardized measure for the RDS. I also employed mediation analyses to investigate why grain imports have such a large detrimental effect on the GDP per capita. The analyses showed that grain imports substantially increased population growth, reduced years of schooling, retarded physical capital formation, and lowered the per hectare grain output. These mediator variables could explain approximately 80% of the estimated damage of grain imports on GDP per capita.

To estimate the total effect of the GR on income divergence, I had to obtain the GR's direct effect via HYV adoption. The direct effect can be estimated by replicating the estimation of Gollin et al. (2018), using the dataset of the current study. Similar to Gollin et al. (2018), the estimation showed that a 1% increase in the HYV adoption rate led to a 1.53 percentage point increase in the GDP per capita. The sum of the estimated indirect and direct effects indicates that the GR had substantially raised the cross-country income divergence. Among the 78 developing countries examined, 38 benefited from the GR, whereas the remaining 40 were damaged. The average gain of the benefited countries was 66.2 percentage points (of the 1960 GDP per capita) by 2000, and the average loss of the damaged countries was 44.3 percentage points.[8] Therefore, if the 1960 incomes were the same for the two groups of countries, the GR could increase their income ratio by 1.9 from 1960 to 2000. A counterfactual analysis shows that removing the effect of the GR could eliminate most of the income divergence observed between these two groups of countries since the 1960s.

In addition to identifying the origin of income divergence, this study also makes the following three contributions to the literature. First, it answers a question central to the development policies of most developing countries: whether agricultural growth is still necessary in a world with declining food prices? Although the conventional view is that

[8] The estimated damage of the GR is consistent with the observation that many countries with a low HYV adoption rate experienced a large decline in the GDP per capita during the GR (Figure B4).

agricultural development is necessary for long-run economic development,[9] there is a growing debate over whether conventional wisdom still applies in a more integrated global environment with falling food prices (Hart 1998, World Bank 2007). Since the food prices today are determined more by border prices, declining world food prices may reduce the need to invest in agriculture. Unfortunately, this study shows that grain imports substantially retarded income growth in developing countries falling behind in agriculture and led them to specialize in unpromising extractive industries. Therefore, even in an integrated global environment, developing countries generally cannot bypass an agricultural revolution to successfully launch their economic transformations.

This study also contributes to relieve the concern that domestic agricultural growth may retard the economic development for *open* economies. Some theoretical models (e.g., Matsuyama 1992) predict that agricultural productivity growth of an open economy may strengthen its comparative advantage in agriculture, thus delaying the transition to industry and harnessing long-run economic growth. No persuasive evidence, however, has been provided to support or reject this prediction.[10] This study provides strong evidence suggesting that agricultural growth and the resulting grain *exports* accelerate, instead of delaying, the development process of open economies. This finding is rationalized by the fact that agricultural growth promotes human capital formation and learning-by-doing in manufacturing, which, in turn, enable the country to also gain a comparative advantage in manufacturing. Note that this finding is based on the background that there exist equally or less developed trade partners, so that a country that gained advantage in agriculture could easily gain a comparative advantage in manufacturing and lead the trade partners to specialize in extractive industries.

Finally, this study contributes to the literature that identifies trade as an important source of income divergence. For example, Krugman and Venables (1995) and Baldwin et al. (2001) found that the reduction in transportation costs and the associated expansion in trade generated geographically based industrialization and divergence; Galor and Mountford (2008) established that trade enlarges income differences by

[9] This view has been formalized by recent theoretical studies (e.g., Gollin et al. 2002, Restuccia et al. 2008, Vollrath 2011) and supported by abundant empirical evidence (e.g., Foster and Rosenzweig 1996, Bustos et al. 2016, Gollin et al. 2018).

[10] Although existing empirical studies generally find a positive effect of agricultural growth on economic development, most of these studies were conducted in the context of closed economies. In addition, the widely observed positive correlation between agricultural productivity and economic performances across open economies could not be taken as evidence relieving this concern because agriculture growth is generally endogenous to economic growth.

increasing fertility and reducing education in less developed countries; and Young (1991) illustrated that opening up to trade may inhibit learning-by-doing in less developed economies that may then specialize in more traditional production activities. This paper is in line with these studies because it finds that trade enlarges income divergence by asymmetrically affecting fertility, education, learning-by-doing, and specialization. The major difference is that this study attributes the income-divergency effect of trade to the underlying asymmetric effect of the GR.

The rest of the paper is organized as follows. Section 2 presents four key facts of the GR. Section 3 provides a simple theoretical framework for understanding the impact of the GR on income divergence. Section 4 estimates the effect of GR on trade. Section 5 estimates the effect of the GR-caused grain trade on income and identifies the mechanisms of the effect. Section 6 evaluates the total effect of the GR on income divergence across developing countries. Concluding remarks are provided in Section 7, followed by four appendices.

2. Four Key Facts about the Green Revolution

There are four facts critical for the identification in this study: (1) the GR was largely exogenous to individual developing countries; (2) productivity gains from the GR substantially differed across countries; (3) world grain prices remarkably declined since the GR; and (4) grain imports significantly increased in countries less suitable for cultivating HYVs since the GR.

First, the GR was plausibly exogenous because its timing was determined by international institutions and its intensity was determined largely by the local agro-climatic suitability of major GR crops. The GR was a set of technology transfer initiatives that increased agricultural productivity in the developing world, beginning, most markedly, in the mid-1960s (Hazell 2009). International institutions, most importantly, the Consultative Group on International Agricultural Research (CGIAR), played a critical role in the GR. The crop productivity growth in the developing world was driven, by a large part, by crop germplasm improvements in CGIAR centers that were then transferred to national agricultural programs for adaptation and dissemination (Conway 2012). The GR's success was based on scientific advances already made in the developed world for three major staple crops: rice, wheat, and maize (Hazell

2010).[11] Therefore, countries with agro-climatic conditions more suitable for cultivating the three major GR crops gained more agricultural productivity from the GR (Evenson and Gollin 2003a).

Second, productivity gains from the GR widely differed across countries with different HYV adoption rates. As presented in Figure B1, for a sample of 78 developing countries, the average yield of the top 10 major food crops increased by 0.93 tons per hectare from 1965 to 2000, which equals to a 72% increase as compared to the average yield of 1965. Productivity gains, however, were substantially different across countries. For example, the per hectare output increased by 1.9 tons in the 10 countries with the highest HYV adoption rates but only increased by 0.4 tons in the 10 countries with the lowest HYV adoption rates. A simple regression indicates that a 10% increase in the HYV adoption rate leads to 0.15 tons higher per hectare output.

Third, the GR had significantly reduced global real food prices. Evenson and Gollin (2003a) estimated that without the GR, world grain prices would have been 35–66% higher in 2000. Figure B2 shows that the average price index for the three GR crops (rice, wheat, and maize) dramatically declined from 38.5 in 1960 to 16.7 in 2000. The price decline was not driven by the low food demand because the world population doubled from 3.0 billion to 6.1 billion during this period. In addition, Table B1 shows that the domestic grain prices of developing countries are highly correlated with the world grain prices, even for relatively closed countries.

Finally, the net grain imports have substantially increased since the GR in developing countries less suitable for cultivating the HYVs. Somewhat counterintuitive, many developing countries heavily depend on food imports for consumption (FAO 2000, McCalla 2001). According to the FAO Statistical Databases, for the 78 developing countries examined in this article, as many as 65 were net importers of the 10 major food crops in 2000, and the (net) import-consumption ratio exceeded 5% in 61 countries and exceeded 20% in 36 countries. As presented in Figure 2, for developing countries with an HYV adoption rate lower than the average of the developing world (i.e., the disadvantaged countries), the average import-consumption ratio increased from 5.9% in 1965 to 26.9% in 2000. Similarly, for the one-third most disadvantaged countries, the ratio increased from 13.1% to 37.0%. In sharp contrast,

[11] The CGIAR research programs focused on other major crops, such as cassava, sorghum, and millets, were introduced decades later (Renkow and Byerlee 2010).

for advantaged countries, the ratio declined from 13.2% to 4.9% over the same period.

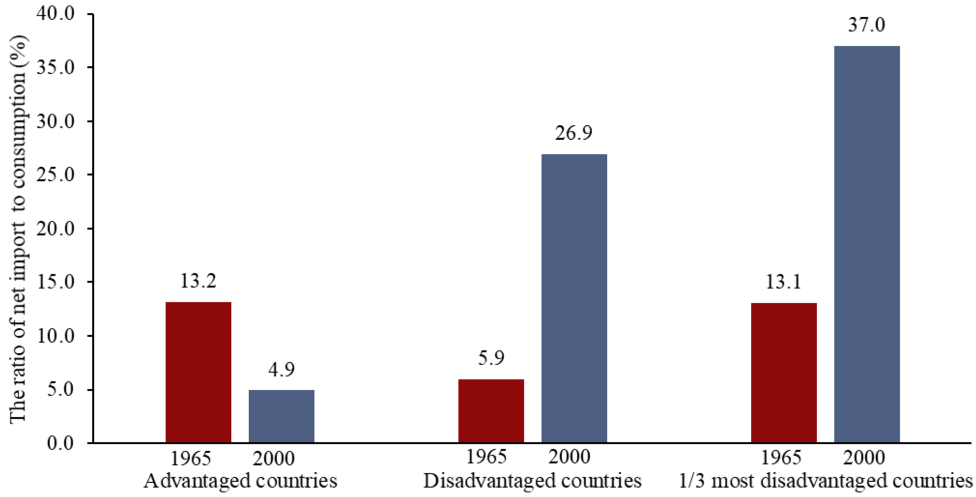

Figure 2. The import-consumption ratio of 10 major food crops

Notes: The figure presents the net import to consumption ratio of the 10 major food crops for 78 developing countries in 1965 and 2000. The ratio was calculated separately for the advantaged countries, the disadvantaged countries, and the 1/3 most disadvantaged countries. The advantaged (disadvantaged) countries are defined as those with an HYV adoption rate higher (lower) than the harvesting-area-weighted average adoption rate across the sample countries. The data were derived from the FAO Statistical Databases.

3. Conceptual Framework

This section provides a theoretical framework to understand the impact of the GR on income divergence across countries. Since the contribution of this study is not theoretical, I only present the key predictions of a very simple model based on three well-accepted assumptions. The model assumes two otherwise identical *open* countries, one is suitable for cultivating the HYVs (GR-advantaged) and the other is not (GR-disadvantaged). Each country contains three sectors: mining (e), agriculture (a), and manufacturing (m). The sectoral production functions are

$$Y_e = A_e(\Pi_e)H^{\alpha}N_e^{\alpha}, \quad Y_a = A_a(\Pi_a)H^{\alpha}N_a^{\alpha}, \text{ and } Y_m = A_m(\Pi_m)H^{\alpha}N_m^{\alpha}E^{1-\alpha},$$

where A_i and N_i are the total factor productivity (TFP) and employment, respectively, in sector $i = e, a, m$; H is the per capita human capital; E is the raw material produced from mining; Π_i is the historical total output from sector i (will be explained later); and $\alpha \in (0,1)$. Farmland and nature resources employed in agriculture and mining are normalized to 1. Identical agents consume food (Y_a) and manufactures (Y_m) to derive utility, whereas raw materials produced from mining (Y_e) are only used as inputs in manufacturing (E). Total population is assumed to be

$N = N_e + N_a + N_m$, and the output prices are denoted as p_i . In the competitive equilibrium, wages are equal and markets clearing.

The model depends on three major assumptions to derive implications. First, following the learning-by-doing literature (e.g., Young 1991, Grossman and Helpman 1991), it assumes that learning-by-doing in manufacturing is the driving force of economic growth (**Assumption I**). Specifically, it assumes that manufacturing TFP increases with the historical total output ($\partial A_m / \partial \Pi_m > 0$), agricultural TFP is unaffected by the historical total output ($\partial A_a / \partial \Pi_a = 0$), and mining TFP declines with the historical total output ($\partial A_e / \partial \Pi_e < 0$).[12] Second, it follows the standard literature on human capital, fertility, and growth (Becker and Lewis 1973, Becker et al. 1990) to assume that higher returns to human capital lead to lower fertility and higher investments in human capital (**Assumption II**). For simplicity, it assumes that human capital increases with the marginal output of human capital ($\partial H / \partial (\partial p_i Y_i / \partial H) > 0$) and fertility (and thus population) declines with human capital ($\partial N / \partial H < 0$). Finally, it follows the literature on structure change (Laitner 2000, Gollin et al. 2002) to assume a period utility function that embodies the Engel's law, which shifts demand from agricultural to manufactured goods as income growth (**Assumption III**). As most clearly demonstrated by Gollin et al. (2002), Engel's law implies that increases in per capita agricultural output reduce food prices and shift labor out of agriculture.

Because the model assumes that only one of these two otherwise identical countries is suitable for cultivating the HYVs, no trade could occur between them before the GR, and the GR only directly affected agricultural TFP in the GR-advantaged country. To facilitate the analysis, I denote variables as V^O for both countries in the case of no GR, as V^A and V^D for the GR-advantaged and GR-disadvantaged countries, respectively, after the GR but before they trade with each other, and as V^{A*} and V^{D*} in the post-GR trade equilibrium.

PROPOSITION 1. *The GR increase income per capita in the GR-advantaged country by improving agricultural and manufacturing productivity, reducing population growth,*

[12] Manufacturing in developing countries has a high potential of learning because technologies from the developed world are readily available for them to learn. Agriculture naturally has a low potential of learning because its productivity is mainly determined by factors unaffected by practice, such as sunshine and rainfall. Mining is subjected to "negative learning" in the sense that natural resources are depletable, and the extraction cost increases with the historical total output.

and enhancing human capital accumulation. For the GR-advantaged country, the GR leads to higher agricultural productivity ($A_a^A > A_a^O$), which increases the agricultural output and shifts labor out of agriculture (*Assumption III*). Higher agricultural productivity also leads to higher returns to human capital ($\partial Y_a/\partial H$), which reduces fertility and increases human capital accumulation (*Assumption II*). Higher human capital and more labor inputs (shifted out from agriculture) lead to higher manufacturing output, which raises manufacturing TFP via learning-by-doing (*Assumption I*).

PROPOSITION 2. *The GR leads the GR-disadvantaged country to import food and manufactures and to export raw materials*. In the GR-advantaged country, the higher agricultural productivity reduces food prices ($p_a^A < p_a^O$), and the higher manufacturing productivity reduces manufacture prices ($p_a^A < p_a^O$) and leads to higher demand for raw materials (E), which increases raw material prices ($p_e^A > p_e^O$). The GR-disadvantaged country is not directly affected by the GR ($V^D = V^O$), so $p_e^A > p_e^D$, $p_a^A < p_a^D$, and $p_m^A < p_m^D$. Therefore, the disadvantaged country will import food and manufactures and will export raw materials until $p_i^{A*} = p_i^{D*}$.

PROPOSITION 3. *The GR-induced trade reduces the per capita income in the GR-disadvantaged country by reducing the prices of food and manufactures, reducing manufacturing productivity growth, increasing population growth, and reducing human capital formation.* For the GR-disadvantaged country, the GR-induced trade reduces its prices of food and manufactures ($p_a^{D*} < p_a^D$, $p_m^{D*} < p_m^D$) and increases its prices of raw materials ($p_e^{D*} > p_e^D$). These price changes reallocate labor from agriculture and manufacturing to mining, which increases the mining output and reduces the agricultural and manufacturing output. A lower manufacturing output and a higher mining output lead to lower productivity growth in these two sectors (since $\partial A_m/\partial \Pi_m > 0$ and $\partial A_e/\partial \Pi_e < 0$, *Assumption I*). A lower TFP in manufacturing and mining lead to lower returns to human capital, which increase population growth and reduce human capital accumulation (*Assumption II*). Although agricultural TFR is not directly affected, the lower food prices reduce the per capita agricultural income.

Note that this theoretical framework is most closely related to that of Matsuyama (1992). By also assuming learning-by-doing in manufacturing and Engel's law in consumption, the model of Matsuyama (1992) predicts that an open economy with higher agricultural productivity tends to specialize in agriculture and, thus, is delayed in long-run economic growth. The model of this article arrives at an opposite prediction due to two additional assumptions. First, this article assumes that agricultural growth promotes human capital accumulation, which allows the economy advantaged in agriculture to also gain an advantage in manufacturing. Second, this article assumes three sectors, instead of the two sectors (agriculture and manufacturing) assumed in Matsuyama (1992), and thus allows the economy disadvantaged in both agriculture and manufacturing to specialize in the third sector (mining). Consistent with these assumptions, this study shows evidence that the GR leads the GR-advantaged countries to export more grain and manufactured goods and leads the GR-disadvantaged countries to export more raw materials.

4. The Effect of the Green Revolution on Trade

This section first constructs a measure of the differential effects of the GR on grain productivity across developing countries: the relative disadvantage in adopting HYVs. This measure is then used to examine the effect of the GR on the trade flows of grain, manufactures, and raw materials. The estimations confirm the prediction that the GR leads developing countries disadvantaged in adopting HYVs to import more grain and manufactures and to export more raw materials.

4.1 Data

This article mainly depends on data from 78 developing countries (listed in Table A1) from 1960 to 2000, in five-year intervals. The 78 countries accounted for approximately 90% of the developing-world population in 1960. This sample is chosen based on the availability of the HYV adoption rate data from Evenson and Gollin (2003b).[13] The data on GDP and population were derived from the Maddison Project Database 2018, and the trade data were from the FAO Statistical Databases and the World Development Indicators. Detailed data sources of all variables used in this study are presented in Table A2. The key variables will be detailed when introduced in the analysis, and their summary statistics are presented in Appendix B1. In robustness

[13] Evenson and Gollin (2003b) provide the HYV adoption rate data for 91 developing countries from 1960 to 2000. From this dataset, I excluded six countries where the GDP or grain trade data were unavailable and seven countries where the 1960 population was smaller than 1 million.

checks, the study sample will be extended to also include developed countries and/or continuous years from 1950 to 2016.

4.2 The Relative Disadvantage in Adopting HYVs

A natural measure of the GR's differential effects on grain productivity across countries is the relative disadvantage in adopting HYVs (RDS), which can be calculated as the average HYV adoption rate of the developing world minus the HYV adoption rate of an individual country (a standardized RDS will also be used in the robustness check). The RDS is constructed based on the HYV adoption rates of 10 major food crops (wheat, rice, maize, barley, potatoes, millet, sorghum, cassava, dry beans, and groundnut) compiled by Evenson and Gollin (2003b), which is the most complete dataset on HYV adoption to the best of my knowledge. The HYV adoption rate of a crop is the share of the crop's harvested area planted with HYVs. The 10 crops accounted for 96% of the total output of staple crops in the 78 sample countries (calculated as the average during 1960–2000, based on the FAO data).

To construct the RDS, I first calculate the *country-level* weighted-average adoption rate of the 10 crops, as follows:

$$HYV_{it} = \frac{\sum_{j=1}^{J} HYV_{it}^{j} \times Area_{it}^{j}}{\sum_{j=1}^{J} Area_{it}^{j}} \quad ,$$

where HYV_{it}^{j} is the share of the harvested area of crop j planted with HYVs in year t and country i, and $Area_{it}^{j}$ is the harvested area of crop j. The RDS is then calculated as follows:

$$RDS_{it} = \overline{HYV}_{t} - HYV_{it} \quad ,$$

where $\overline{HYV}_{t}$ is the weighted-average adoption rate across the 78 countries:

$$\overline{HYV}_{t} = \frac{\sum_{i=1}^{I} HYV_{it} \times TotalArea_{it}}{\sum_{i=1}^{I} TotalArea_{it}} \quad ,$$

with the total harvested area of the 10 crops in country i and year t ($TotalArea_{it}$) as the weightings.

According to the construction, countries with a higher RDS are more *disadvantaged* in adopting HYVs. Figure 3 presents the variation in the RDS across regions and over time. It shows that the RDS was virtually zero for all regions (indicating no relative disadvantage) before 1965 but varied widely after that. The relative disadvantage across regions generally enlarged over time. East and SE Asia and the Pacific (red line) and South Asia (dark red line) became increasingly advantaged during the GR (i.e., with a more negative RDS), whereas other regions become increasingly disadvantaged (although the RDS in Latin America and the Caribbean declined slightly after 1980). The most disadvantaged region was Sub-Saharan Africa, where the RDS was as high as 46.9 in 2000.

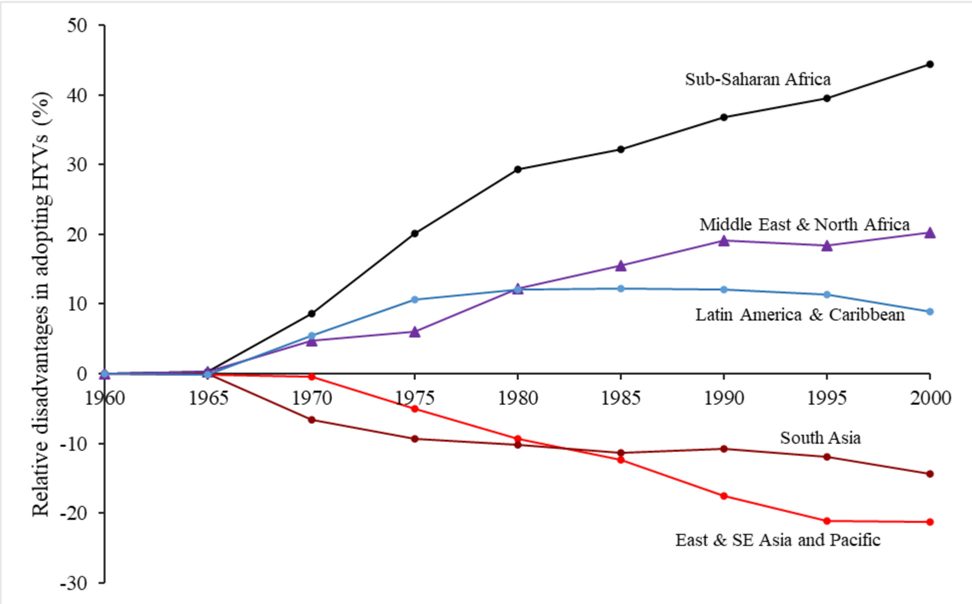

Figure 3. Chronological and regional variations in the relative disadvantage in adopting HYVs (RDS)

Notes: The RDS is calculated as the difference between the developing world (harvesting-area-weighted) average HYV adoption rate and the adoption rate of each country. The regional average RDS is calculated as the (harvesting-area-weighted) average RDS for all sample countries within each region. The data for HYV adoption rates were derived from Evenson and Gollin (2003b).

4.3 Identification Strategy

With the RDS in hand, I estimate the effect of the GR on trade as follows:

$$\ln Imp_{it} = \nu_i + \tau_t + \alpha_1 RDS_{it} + Z_{it}\lambda + \varepsilon_{it} \quad , \tag{1}$$

where $\ln Imp_{it}$ denotes three dependent variables: the natural log of *net* import values (in 2011US$) of grain, manufactures, *or* raw materials in country i and year t.[14] The net grain import values are calculated as the sum of the net import values of the *10 major food crops*; the net manufacture import values are the sum of *chemicals, basic manufactures, machinery and transport equipment, and miscellaneous manufactured*

[14] The dependent variables are the total, instead of per capita, imports because the GR-induced imports significantly increased the population growth (Table 3). If the net import value is negative (i.e., the country is a net exporter), the natural log is calculated as $-\ln|Imp_{it}|$.

goods; and the net raw material import values are the sum of *fuel, ores, metals, and agricultural products besides the 10 major crops*. Z_{it} is a vector of control variables (and will be detailed in the estimation); v_i and τ_t denote the country-fixed effects and year fixed effects, respectively; α_1 and λ are coefficients; and ε_{it} is the error term.

The coefficient of interest, α_1, captures the causal effect of a 1% increase in the RDS on percentage changes in net imports, based on the assumption that the RDS is exogenous. This assumption is supported by the fact that, as detailed before, the GR's timing is determined by international institutions, and its intensity is largely determined by the local agro-climatic suitability for cultivating the major GR crops. In addition, the model substantially reduced potential endogeneity bias from omitted variables by including country and year fixed effects: the country-fixed effects account for the confounding effects of any time-invariant factors, whereas the year fixed effects account for any annual shocks that are common across countries.

However, two potential sources of endogeneity concern still exist. First, it is possible that both the RDS and imports are affected by omitted country-specific, time-varying factors (omitted variables), which cannot be accounted for by the fixed effects. For example, both the RDS and grain imports are possibly affected by country-specific evolution of food demand caused by unobservable time-varying factors. Second, the real adoption rate of HYVs (and thus the RDS constructed from it) could be directly affected by imports (reverse causation). For example, it is possible that countries import more grain have a lower incentive to adopt HYVs and thus end up with higher RDS.

To address the endogeneity concerns, I constructed a plausibly exogenous IV for the RDS. The IV is constructed based on cross-country variation in agro-climatic suitability for growing HYVs and on the differentiated timing of the development of HYVs for different crops. Specifically, as detailed in Appendix B2, the IV is constructed in four steps. First, I derived each country's agro-climatic suitability for growing HYVs of the 10 crops from the Global Agro-Ecological Zone dataset computed by FAO. The agro-climatic suitability is measured by the highest attainable yield, which is estimated based on the local climatic conditions using complex biological models. Second, in a panel model with country and year fixed effects, I regress the real HYV adoption rate of each crop on the interactions between the crop's agro-climatic suitability and a full set of year dummies, which capture the differentiated timing of the development of

HYVs. Third, I predict the HYV adoption rate of each crop in each year based on the estimates of the panel model and, then, use the predicted values to calculate the country-level predicted adoption rate of HYVs. Finally, I construct the predicted RDS (pRDS) based on the predicted country-level HYV adoption rates.

The pRDS is a good IV because it is strongly correlated with the RDS but plausibly uncorrelated with other determinants of the outcome of interest, conditional on the fixed effects. The cost of purchasing HYV seeds is independent of climate; thus, the net return of adopting them increases with the agro-climatically attainable yield. Therefore, countries with higher attainable HYV yields should have higher adoption rates. As presented in Figure B5, the predicted RDS is indeed positively and strongly correlated with the observed RDS. Equally important is that a country's agro-climatic conditions should not be affected by the outcome of interest (reverse causality) or by the omitted time-varying determinants of the outcome of interest (omitted variables). Based on similar arguments, the agro-climatic suitability has been frequently used to construct IVs for agricultural productivity in the literature (e.g., Nunn and Qian 2011, Bustos et al. 2016), and the IV construction in this study is the most similar to that of Gollin et al. (2018).

With the IV in hand, the two-stage least squares (2SLS) estimate of α_1 from model (1) can be obtained. The first-stage of the 2SLS estimation is as follows:

$$RDS_{it} = \nu_i + \tau_t + \gamma_1 pRDS_{it} + Z_{it}\eta + \upsilon_{it} \quad ,$$

where $pRDS_{it}$ is the predicted RDS in country i and year t, and all other variables are defined as above. Notice that, depart from the standard 2SLS regressions, here, I use a generated IV. According to Wooldridge (2010, p.124), parameter estimates in 2SLS regressions with generated instruments are asymptotically distributed as in standard 2SLS regressions; thus, the standard errors of the 2SLS estimate of α_1 are asymptotically valid.

4.4 The Estimation Results

Table 1 presents the estimates of model (1). The estimation results confirm the prediction that for countries disadvantaged in adopting HYVs, the GR increased the net imports of grain and manufactures and increased their net exports of raw materials. Specifically, columns 1–4 report the estimated effect of the RDS on net grain imports. The OLS estimates in column 1 suggest that a 1% increase in the RDS leads to 8 percentage points higher grain imports, and this effect is statistically significant at the 1% level. Because the average RDS for the disadvantaged (advantaged) countries was 39.1% (-16.9%) in 2000, this estimate implies that the GR increased grain imports (grain exports) by 313 percentage points (135 percentage points) for an average disadvantaged (advantaged) country from 1960 to 2000.[15,16] Column 2 reports the 2SLS estimates using the predicted RDS as the IV for the RDS. The 2SLS estimate is identical to the OLS estimate, confirming that the RDS is plausibly exogenous. Column 3 controls for eight potential confounding factors and obtains nearly identical estimates, suggesting that the finding is not driven by omitted variables.[17] Column 4 excludes the (net) grain-exporting countries in 2000 from the sample and finds a large effect, indicating that the relationship is primarily driven by the grain-importing countries. In addition, Appendix B3 provides the falsification tests to show that the RDS had no effect on grain imports before the GR.

The estimates presented in columns 5–8 indicate that the RDS has a significantly positive effect on the net import of manufactures, and the estimates presented in columns 9–12 indicate that the RDS has a significantly *negative* effect on the net import of raw materials. These findings are consistent with the prediction that the GR leads the GR-disadvantaged countries to increase their net import of manufactures and to increase the net *export* of raw materials. These estimated effects are also sizeable. The 2SLS estimates reported in columns 6 and 10 suggest that a 1% higher RDS increases the net import of manufactures by 9 percentage points and increases the net export of raw materials by 10 percentage points. These estimates are consistent with the observations from the data that most GR-disadvantaged countries have experienced substantial increases in the net import of manufactures and in the net export of raw materials since the GR.

[15] The GR-induced grain imports account for approximately one-third of the observed increase in grain imports over this period. As presented in Appendix Figure B3, the *log* net grain imports increased by 2.5 over this period for an average disadvantaged country, which corresponds to a roughly eleven-fold increase in net grain imports (i.e., $\exp(2.5)-1=11.18$).

[16] The estimated percentage effect is much larger in the disadvantaged countries because the average size of the disadvantaged countries is much smaller than the average size of the advantaged countries (including countries such as India and China). A calculation shows that the total GR-caused grain imports and exports from these two groups of countries were approximately equal each other.

[17] The control variables used are *log GDP per capita, log population, the share of agriculture in GDP, the dummy of landlocked, soil rooting condition index, soil nutrient index, yearly mean temperature, and yearly total precipitation*. The time-invariant control variables (i.e., *the dummy of landlocked, rooting condition index, and nutrient index*) are interacted with a full set of year dummies. Details of these control variables are presented in Table A2.

Table 1. Effect of the relative disadvantages in adopting HYVs on trade

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Log net grain imports				Log net manufacture imports				Log net raw material imports			
	OLS	2SLS	2SLS	2SLS	OLS	2SLS	2SLS	2SLS	OLS	2SLS	2SLS	2SLS
RDS	0.08***	0.08***	0.08***	0.10***	0.03***	0.09***	0.08***	0.11***	-0.06***	-0.10***	-0.20***	-0.26***
(IV=PRDS)	(0.02)	(0.02)	(0.03)	(0.03)	(0.01)	(0.02)	(0.03)	(0.03)	(0.02)	(0.02)	(0.05)	(0.06)
Eight control variables			Yes	Yes			Yes	Yes			Yes	Yes
Net grain exporter only				Yes				Yes				Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage *F*-statistic		47.4	95.6	189.8		21.5	38.1	103.9		19.4	18.1	51.8
Observations	702	702	675	594	402	402	388	336	374	374	365	318
R-squared	0.665	0.665	0.673	0.554	0.724	0.656	0.751	0.618	0.824	0.813	0.759	0.725

Notes: The table presents the estimates of model (1). The eight control variables are log GDP per capita, log population, the share of agriculture in GDP, the dummy of landlocked, soil rooting condition index, soil nutrient index, yearly mean temperature, and yearly total precipitation; the time-invariant control variables (i.e., the dummy of landlocked, rooting condition index, and nutrient index) are interacted with a full set of year dummies. The sample sizes are smaller when these control variables are included because the data on the share of agriculture in GDP are missing for three countries. The first-stage *F*-statistic reported is the Kleibergen-Paap Wald F-statistic. The standard errors (in parentheses) are clustered at the region-year level, and the regions refer to the five geographic areas presented in Figure 3. Significance levels are *** p<0.01, ** p<0.05, * p<0.1.

Note that the estimated effects of the RDS on the trade of manufactures and raw materials are less credible than that on the trade of grain for two reasons. First, although there is a direct link between the RDS and grain trade, the connection between the RDS and the trade of other products indirectly works through grain. As such, the estimated effects on the trade of non-grain products are potentially more vulnerable to the omitted variable bias. This concern is confirmed by the large change in the 2SLS estimate when additional control variables are included in column 11 (compared to column 10). Second, the data on the trade of non-grain products are unavailable in the early years for numerous developing countries; the sample sizes are approximately 40% smaller in columns 5–12 than in columns 1–4. As such, the estimated effects in columns 5–12 are potentially less representative of the developing world. Nevertheless, the 2SLS estimates are still sufficiently consistent for us to draw a qualitative conclusion that the GR had led the GR-disadvantaged countries to significantly increase manufacture imports and to significant increase raw material *exports*.

Fortunately, the next section only needs to use the GR-induced grain trade (but not the trade of other products) as the intensity measure of the GR's effect through trade. This is because the GR directly affects the cross-country relative grain productivity (and thus grain trade), but it only indirectly affects the relative productivity of other products through affecting grain productivity. Therefore, using grain trade as the intensity measure could capture the GR's effect through trade of other products. In Appendix C3, I also estimate the effect by using the trade of manufactures and raw materials as the intensity measures. The estimation confirms that the imports of manufactures and the exports of raw materials substantially reduced the GDP per capita in countries disadvantaged in adoption HYVs. Note that if grain trade does not capture all effects of the GR through the trade of non-grain products, the main estimates presented in this study tend to underestimate the effects of the GR on income through trade.

5. The Effect of Grain Imports on GDP per Capita

This section estimates the effect of the GR-induced grain imports on income per capita. The results confirm the theoretical prediction that the GR-induced grain imports significantly reduced the per capita income in countries disadvantaged in adopting HYVs. This section also demonstrates that the detrimental effect of grain imports on income per capita mainly comes from the grain-import-caused faster population growth, slower human capital formation, and lower physical capital investment. Appendix C3 shows that the GR-induced trade of manufactures and raw materials also significantly reduced the per capita income in the GR-disadvantaged countries.

5.1 Identification Strategy

The model used to estimate the impact of grain imports on income is as follows:

$$\ln y_{it} = v_i + \tau_t + \beta_1 \ln Imp_{it} + Z_{it}\lambda + \mu_{it} \quad (2)$$

where $\ln y_{it}$ is the log real GDP per capita (in 2011 US$) in country i and year t; $\ln Imp_{it}$ is the log net grain import defined before; Z_{it} is a vector of control variables (will be introduced in the estimation); v_i and τ_t denote the country and year fixed effects, respectively; β_1 and λ are coefficients; and μ_{it} is an error term. The country-fixed effects account for the confounding effects of any time-invariant factors and the year fixed effects account for any annual shocks that are common across countries.

The OLS estimate of β_1 cannot be interpreted as the causal effect of grain imports on income before the following two issues are addressed. The first issue is the omitted variables. Although the model includes country and year fixed effects, the estimate of β_1 could still be biased by the omitted country-specific, time-varying factors that affect both grain imports and income, such as changes in transportation costs. The second issue is the reverse causation. For example, higher incomes (and thus wages) may promote grain imports by increasing food demand and reducing agricultural labor supply. If this is the case, the positive reverse effect of income on grain imports tends to offset the negative effect of grain imports on income.

I attempt to address these endogeneity issues by using RDS (or predicted RDS) as the IV for grain imports in the 2SLS estimation of model (2). As detailed above, conditional on the country and year fixed effects, the RDS is plausibly exogenous in the sense that it is neither correlated with any other country-specific, time-varying determinants of income (omitted variables) nor affected by income (reverse causation). In addition, the last section shows that the RDS is strongly and robustly correlated with grain imports. Therefore, the RDS is potentially a good IV for grain imports. Very similar results have been obtained when using the *predicted* RDS, which is even more likely to be exogenous, as the IV. Moreover, in robustness checks, I also use the distance to major grain-exporting countries as an alternative IV and find comparable results.

5.2 Baseline Estimates

Column 1 of Table 2 presents the OLS estimate of model (2). It suggests that a 1 percentage point increase in net grain imports reduces the GDP per capita by 0.02 percentage points, and this effect is statistically significant at the 1% level. However, the OLS estimate is likely subject to an endogeneity bias. Column 2 presents the 2SLS estimate of model (2) using the RDS as the IV for grain imports. The 2SLS estimate is substantially larger than the OLS estimate, suggesting that the OLS estimate is downwardly biased (potentially due to the aforementioned reverse causality). The 2SLS estimate indicates that a 1 percentage point increase in the net grain imports reduces the GDP per capita by 0.14 percentage points.

Recall that for an average disadvantaged (advantaged) country, the GR had increased grain imports (grain exports) by 313 percentage points (135 percentage points) by 2000. Therefore, the 2SLS estimate from column 2 of Table 2 indicates that the GR-induced grain trade reduced (increased) the GDP per capita in an average disadvantaged (advantaged) country by 43.8 percentage points (18.9 percentage points) by 2000.[18] If the average GDP per capita were the same for the disadvantaged and advantaged countries before the GR, the GR-induced grain trade could have led to an income ratio of 2.1 between these two groups of countries by 2000, which is comparable to the actual income divergence observed between high HYV adoption and low HYV adoption countries in Figure 1. A more detailed analysis of the effects of the GR on income divergence will be presented in Section 6.

[18] The estimated percentage effect should be interpreted relative to the GDP per capita in the base year (1965) when the RDS was zero. For example, the grain trade reduced GDP per capita by 43.8 percentage points by 2000, which should be interpreted as the GDP per capita being reduced by 2000 equals 43.8 percentage points of the GDP per capita in 1965.

Table 2. The effect of grain imports on the GDP per capita

Dependent variable: log real GDP per capita	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	OLS	2SLS	2SLS	2SLS	2SLS	2SLS	2SLS
Log net grain imports	-0.02***	-0.14***	-0.13***	-0.14***	-0.09***	-0.09***	-0.20***
	(0.00)	(0.05)	(0.02)	(0.04)	(0.02)	(0.02)	(0.06)
IV	No IV	RDS	RDS	pRDS	Distance	pRDS, Distance	pRDS
Four time-invariant controls * year dummies			Yes	Yes	Yes	Yes	Yes
Including developed countries and more sample years					Yes		
Excluding net grain exporters							Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage *F*-statistic		33.9	32.9	16.0	281.8	15.9	14.6
Hansen *J*-statistic (*p*-value)						2.18 (0.14)	
Observations	702	702	693	693	6193	693	612
R-squared	0.935	0.841	0.863	0.858	0.916	0.910	0.816

Notes: The four time-invariant controls are the log 1960 GDP per capita, the first official language, colonizer, and landlocked. The sample size is smaller when these controls are included due to missing values of some controls. The study sample in column 5 includes 118 developing and developed countries in continuous years from 1950 to 2016. The first-stage *F*-statistic reported is the Kleibergen-Paap Wald *F*-statistic. The standard errors (in parentheses) are clustered at the region-year level. Significance levels are *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5.3 Robustness Tests

This section provides the following robustness tests for the baseline 2SLS estimate in column 2 of Table 2: (1) including a range of control variables; (2) adopting alternative IVs; (3) excluding countries that were net grain exporters; (4) conducting falsification tests; (5) measuring grain imports by the per capita values; (6) using a standardized measure for the relative disadvantage in adopting HYVs; (7) excluding extreme values of grain imports; (8) controlling for linear and quadratic time trends; (9) clustering the error term at different levels; and (10) focusing on sectoral GDP per capita. All these tests support the main finding that grain imports substantially reduced the GDP per capita in the GR-disadvantaged countries.

5.3.1 Control Variables

Column 3 of Table 2 controls for the interactions between a full set of year dummies and four most frequently used time-invariant determinants of income growth: log GDP per capita in the base year (1960), official language, colonizer, and landlocked (see Table A2 for variable definitions). The time-invariant effects of these variables should have been accounted for by the country-fixed effects included in the model. However, countries differing in these factors may have different growth trends, which could bias the estimated effect of grain imports. The differential time trends can be controlled for by the interactions between these time-invariant factors and a full set of year dummies. The 2SLS estimate reported in column 3 is only slightly smaller than the baseline 2SLS estimate in column 2, suggesting that the estimated effect of grain imports on GDP per capita is primarily not driven by the potential differential trends associated with these time-invariant factors.

Note that the model does not control for any time-varying determinants of income to avoid the overcontrol bias. Given that the timing and intensity of the GR is exogenous to individual countries, RDS should not be affected by any time-varying determinants of income. Therefore, any time-varying factors correlated with both the RDS and income could only be a result (but not the cause) of the RDS. In other words, these factors are the mediator variables of the effects of the RDS on income. Controlling for a mediator variable may partly account for the true effect of the RDS on income and lead to the overcontrol bias. The mediation effect of various time-varying income determinants will be examined in Section 5.4.

5.3.2 Alternative Instrumental Variables

Columns 4–6 of Table 2 tests the robustness of the 2SLS estimate to two alternative IVs: the predicted RDS and the bilateral distance between countries. Column 4 uses the predicted RDS, instead of the actual RDS, as the IV in the 2SLS estimation. As detailed before, the predicted RDS is constructed based on the agro-climatically attainable yield of the 10 major crops, instead of the actual HYV adoption rate. Therefore, the predicted RDS is even more likely exogenous (than the actual RDS) in the sense that the agro-climatically attainable crop yield is not affected by any outcomes of interest. The 2SLS estimate using the predicted RDS as the IV is identical to the baseline 2SLS estimate, which confirms that the RDS is indeed exogenous.

Columns 5 and 6 follow the trade literature to use the bilateral distance between countries as the IV for trade. Specifically, I use the distance to the *nearest* top 10 net grain-exporting countries *in each year* as the IV for grain imports. The bilateral distances between countries are derived from the dataset of Mayer and Zignago (2011). Appendix C1 details the construction of the distance IV and shows that the distance IV is strongly and negatively correlated with the grain imports. As presented in column 5, the 2SLS estimate based on the distance IV is about one-third smaller than the baseline estimate, but still suggests that the grain imports significantly reduced the GDP per capita. The smaller estimated effect is likely because it is not just grain trade through which the distance IV affects income.[19] Note that since the distance IV is available for both developing and developed countries in continuous years from 1950 to 2016, the study sample in column 5 is much larger. Column 6 uses both the bilateral distance and the predicted RDS as IVs (and, thus, focuses only on the 78 developing countries from 1960 to 2000) and shows the same estimated effect, suggesting that the IV estimate is not sensitive to the study sample. Comparable results are observed when using the distance to the nearest top 5 or 15 net grain-exporting countries as the IV.

[19] The main analysis of this study does not depend on the distance IV because it affects income not only through grain trade. The trade literature usually uses bilateral distance as the IV for trade value based on the assumption that the geographical distance affects a country's economic outcomes only through trade (e.g., Frankel and Romer 1999). This assumption is valid when the trade is broadly defined to include elements such as FDI and the accompanying technology diffusion. When considering the specific grain trade, however, this assumption is likely invalid. To the extent that the distance IV affects income through trade elements beyond grain trade, the 2SLS estimate could capture the effect of these other trade elements. Because trade elements correlated with distance, such as FDI and technology diffusion, usually have a positive effect on income, the 2SLS estimate based on the distance IV tends to be biased towards the positive end. This explains why the estimated negative effect of grain imports is smaller when using the distance IV.

5.3.3 Excluding Grain-exporting Countries

Column 7 excludes sample countries that were net exporters of the 10 major crops in 2000. It is reasonable for the baseline estimation to include both grain importers and grain exporters because the effect direction of the *net* grain imports is predicted to be the same: grain imports reduce income and grain exports increase income. However, there is a potential concern that the estimated negative association may be mainly driven by the grain-exporting countries. This is possible considering that, as presented in Figure B3, several large GR-advantaged countries dominated the increase in grain exports among the developing countries. If this concern is valid, the baseline estimate cannot be used to support the major argument of this study that the GR hinders income growth in the GR-disadvantaged countries through increasing their grain imports. Fortunately, column 7 eliminates this concern by showing that the negative effect is even larger when the grain-exporting countries are excluded from the sample. This finding also suggests that the marginal damage from grain imports is larger than the marginal benefit from the grain exports.

5.3.4 Falsification Tests

A crucial underlying assumption of the 2SLS estimation is that, conditional on the country and year fixed effects, the RDS is not correlated with the income trends prior to the GR. Violating this assumption would imply that the RDS is endogenous in the sense that it is correlated with the omitted preexisting income determinants. This assumption can be verified by estimating a flexible version of model (2) that replaces the $\ln Imp_{it}$ by the interactions between the 1965–2000 average RDS ($\overline{RDS_i}$) and a full set of year dummies ($year_t^k$):

$$\ln y_{it} = \nu_i + \tau_t + \sum_{k=1952}^{2016} \beta_k \overline{RDS_i} \times year_t^k + Z_{it}\lambda + \mu_{it} \quad . \tag{3}$$

Because continuous annual data on GDP per capita are available from 1951 to 2016, the flexible model could identify the effect of the average RDS on GDP per capita in each year starting from 1951. If the RDS captures only the effect of the GR, but not the effect of the omitted income determinants correlated with preexisting growth trends, the flexible model should find that the average RDS had no effect on the income prior to the GR.

Figure 4 reports the estimated coefficients $\beta_k s$ together with their 95%

confidence intervals. Consistent with the identification assumption, the estimated coefficients are all close to zero and statistically insignificant prior to the GR (i.e., prior to 1965). The figure also shows that the coefficient starts declining since the GR and becomes significantly negative later on. It confirms the main finding of this article that the GR reduced GDP per capita in developing countries disadvantaged in adopting HYVs.[20] In addition, although the main analysis of this study is based on data until 2000, the flexible regression suggests that the negative effects of the GR lasted at least up to 2016. Very similar estimates were obtained when the average RDS was replaced by the average *predicted* RDS in model (3).

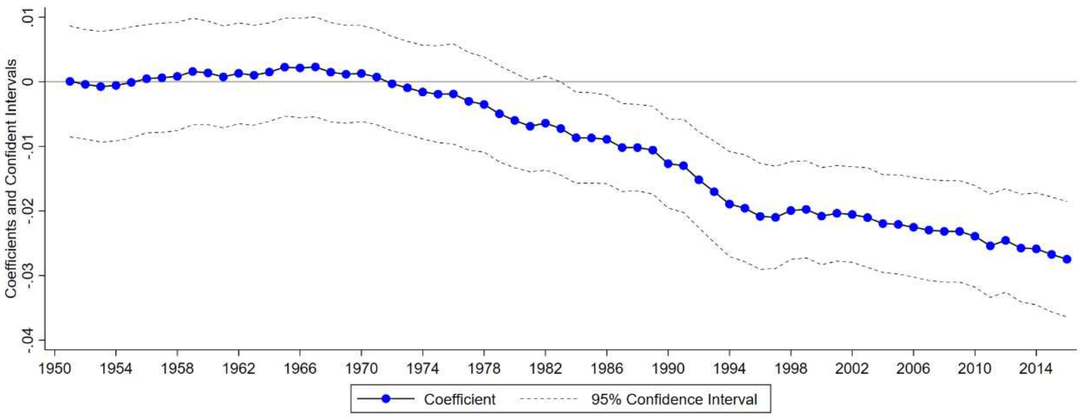

Figure 4. Relationship between the average RDS between 1965 and 2000 and the GDP per capita in each year

Note: Each dot on the solid line is the point estimate of $\beta_k s$ from equation (3), and the broken lines indicate the 95% confidence intervals.

5.3.5 Additional Robustness Tests

Various additional robustness tests of the baseline 2SLS estimate are presented in Appendix C2. The additional robustness tests involve measuring grain imports by the per capita values; using a standardized measure of the relative disadvantage in adopting HYVs; excluding extreme values of grain imports; controlling for linear and quadratic time trends; clustering the error terms at different levels; and focusing on the sectoral GDP per capita. All these robustness tests confirm the baseline finding that the GR-induced grain imports substantially reduced the GDP per capita in countries disadvantaged in adopting HYVs. Appendix C2 also explains why these alternative model settings are not used in the main analysis.

[20] Note that the magnitude of individual point estimates in Figure 4 is difficult to interpret. Because the $\overline{RDS_i}$ is time invariant and the model includes country and year fixed effects, the estimated β_ks must be measured relative to a baseline time-period, which I take to be 1951. Therefore, the absolute level simply tells us the difference in the relationship relative to an arbitrarily chosen baseline.

5.4. Why Grain Imports Reduced Income?

This section attempts to explain why grain imports have such a large detrimental effect on the per capita income. Specifically, I adopt a mediation analysis to investigate if and to which extent the effect of grain imports on income can be explained by a series of potential mediator variables. The standard mediation analysis comprises four steps: first, the total effect of grain imports on income (β_1) is estimated; second, the effect of grain imports on each of the K potential mediators (a_k) is estimated; third, the effect of each mediator on the income (b_k), conditional on grain imports and other mediators, is estimated; and finally, the mediation effect through each mediator ($a_k b_k$) and the proportion of the total effect mediated ($\sum a_k b_k / \beta_1$) are calculated.

Formally, the mediation analysis involves estimating a system of equations:

$$\begin{aligned} z_{it}^1 &= \nu_i + \tau_t + a_1 \ln Imp_{it} + \mu_{it}^1 \\ z_{it}^2 &= \nu_i + \tau_t + a_2 \ln Imp_{it} + \mu_{it}^2 \\ &\vdots \\ z_{it}^K &= \nu_i + \tau_t + a_K \ln Imp_{it} + \mu_{it}^K \\ \ln y_{it} &= \nu_i + \tau_t + c' \ln Imp_{it} + \sum_{k=1}^{K} b_k z_{it}^k + \mu_{it}' \end{aligned} \quad . \tag{4}$$

In the model, z_{it}^k is k's mediator variable, a_k captures the effect of grain imports on mediator k, b_k is the effect of mediator k on the GDP per capita, and c' is the effect of grain imports not mediated. All other variables are as defined before. Each equation includes the country and year fixed effects to account for confounding factors. I estimate equations in model (4) simultaneously using the seemingly unrelated regressions (SUR) that allow the error terms to be correlated across equations.[21] The SUR estimation also facilitates the calculation of the mediation effect, which involves combining the estimates across equations. Finally, to address the endogeneity of grain imports, $\ln Imp_{it}$ in each equation of the SUR is instrumented by the RDS.[22]

---

[21] Very similar results were obtained when estimating the system of equations by structural equation modeling using the Stata package *sem*.

[22] In the SUR, the IV for grain imports is manually included in each equation in four steps: first, regress the log grain imports on the RDS in a panel model with country and year fixed effects; second, calculate the predicted log grain imports from the regression; third, replace the log grain imports in each equation of model (4) by the predicted log grain imports; and finally, fix the standard errors in the SUR by bootstrap with 200 replications. This estimation process is similar to that for manually conducted 2SLS estimation detailed by Cameron and Pravin (2010). The standard errors of the estimated indirect effect are also obtained from bootstrap with 200 replications in order to address the concern that the estimate of the indirect effect may not be normally distributed (Shrout and Bolger 2002). Very similar results are obtained when calculating the standard errors by the traditional delta method.

Table 3. Mechanisms of the Effect of Grain Imports on the Income Per Capita

	(a) Log net grain imports	(b1) Log population	(b2) Crude birth rate	(b3) Years of schooling	(b4) Log capital formation per capita	(b5) Log inward FDI per capita	(b6) Per hectare grain yield	(c) Sum of mediation effects
(1) The effect of log grain imports on each mediator		0.026***	0.949***	-0.137***	-0.211***	-0.409***	-0.186***	
		(0.005)	(0.169)	(0.028)	(0.021)	(0.062)	(0.019)	
(2) The effect of log grain imports and mediators on the log GDP per capita	-0.031***	-0.216**	-0.014***	0.038**	0.256***	0.025***	0.111***	
	(0.012)	(0.089)	(0.003)	(0.016)	(0.020)	(0.007)	(0.022)	
(3) Mediation effect of each variables		-0.006**	-0.013***	-0.005***	-0.054***	-0.010***	-0.021***	-0.109***
		(0.002)	(0.003)	(0.002)	(0.007)	(0.003)	(0.005)	(0.010)
(4) Share of the total effect mediated (%)		4.3	9.3	3.6	38.6	7.1	15.0	77.9

Notes: This table reports the estimation results of model (4) based on seemingly unrelated regressions. Row 1 reports the estimated effect of grain imports on each mediator (a_k), row 2 reports the estimated effect of each mediator and grain imports on income (b_k and c'), row 3 reports the calculated mediation effect of each mediator ($a_k b_k$), and row 4 reports the share of the total effects mediated ($a_k b_k / \beta_1$). All standard errors reported in parentheses are estimated from bootstrap with 200 replications (see Footnote 22 for details). Significance levels are *** p < 0.01, ** p < 0.05, * p < 0.1.

Table 3 reports the estimated mediation effects of six time-varying income determinants that may be affected by the grain imports: the population size, birth rate, years of schooling, capital formation, inward FDI, and per hectare grain yield (see Table A2 for variable definitions).[23] As reported in row 1, the estimated effects of grain imports on the six mediators (a_k) are all statistically significant and are consistent with the theoretical predictions.[24] Specifically, the estimates presented in columns b1–b6 indicate that a one-unit increase in the *log* grain imports increases the population size by 2.6 percentage points, increases the crude birth rate by 0.95 (births per 1,000 people), reduces the average years of schooling by 0.14 years, reduces the per capita physical capital formation by 21.1 percentage points, reduces the per capita inward FDI by 40.9 percentage points, and reduces the per hectare grain yield by 0.19 rice-equivalent tons.

Row 2 presents the effect of mediators on income (b_k) and the remaining effect of grain imports (c'). All mediators have significant effects on income, and the effect of grain imports not explained is only -0.031. Row 3 reports the estimated mediation effect from each mediator ($a_k b_k$). Row 4 reports the share of the total effect mediated by each mediator ($a_k b_k / \beta_1$), which ranges from 3.6% to 38.6% across mediators. The six mediators together explained 77.9% of the total effect. Note that the estimated explanatory power of each mediator should be interpreted with caution because the mediators are likely endogenous and correlated with each other;[25] however, the mechanisms identified (based on the IV estimates in row 1) and the total mediation effect calculated (based on the IV estimates of β_1 and c', i.e., $(\beta_1 - c')/\beta_1 = 77.9\%$) are reasonably credible. Therefore, most of the detrimental effect of grain imports on GDP per capita can be explained by the grain-import-caused faster population growth, slower human and physical capital formation, and lower grain yield.

---

[23] I also examined various other income determinants, such as life expectancy, dependency ratio, and urbanization rate, and found that they have only a negligible mediation effect.

[24] The theoretical model predicts that grain imports increase fertility, reduce human capital formation, and reduce the per hectare agricultural yield. Although the simple model does not include physical capital and FDI, it is straightforward to extend the prediction to them: because grain imports reduce productivity in manufacturing and mining, they should also reduce physical capital investment and FDI by reducing the returns to them.

[25] While grain imports in each equation of model (4) are instrumented by the RDS, providing independent instruments for each of the mediators is difficult. As such, while the estimates in row 1 can be interpreted as causal effects, most estimates in rows 2 and 3 may merely reflect an associative relationship. In addition, because mediators are likely correlated with each other, one mediator may capture the effect of others. For example, a larger population mechanically reduces the per capita capital and FDI; thus, the latter two variables could capture part of the mediation effect of the population size.

6. The Effect of the Green Revolution on Income Divergence

This section evaluates the extent to which the GR could explain the dramatic divergence in income observed across the developing world since the 1960s. As discussed before, the GR could affect a country's per capita income through two channels: the direct effect through increasing the domestic grain productivity (measured by the HYV adoption rate), and the indirect effect through changing the cross-country relative grain productivity (measured by the RDS). Up to this point, I have only estimated the indirect effect, and the direct effect has been estimated by Gollin et al. (2018). This section combines the direct and indirect effects to evaluate the total effect of GR on cross-country income divergence.

Panel A of Figure 5 presents the estimated indirect effect of the GR on GDP per capita through grain trade for each of the 78 sample countries by 2000. The country-level indirect effect is calculated by combining the marginal effect of the RDS on grain imports (column 2, Table 1), the marginal effect of grain imports on GDP per capita (column 2, Table 2), and each country's RDS in 2000. The calculation showed that only 12 countries (from Asia and South America) are benefited from the GR-induced grain trade, whereas the remaining 66 countries are damaged. This finding is consistent with the observation that several large countries (such as China and India) dominated the cultivation areas of HYVs in the developing world and thus dominated the increase in the net grain exports during the GR (see Figure B3). The effect of grain trade ranged from -64 to 37 percentage points across the sample countries, and the (simple) average effect for these countries was -33.1 percentage points by 2000. The significantly negative average effect again reflects the fact that mainly several large countries benefited from the GR-induced grain trade.

Panel B presents the estimated direct effect. I estimated the direct effect by replicating the main estimation of Gollin et al. (2018), which can be rewritten as follows:

$$\ln y_{it} = \nu_i + \tau_t + \eta_1 HYV_{it} + \mu_{it} \quad , \qquad (5)$$

where all variables are as defined above. In the estimation, the endogeneity of the HYV adoption rate (HYV_{it}) is addressed using the predicted HYV adoption rate (see Appendix B2) as the IV. As presented in Appendix D, similar to Gollin et al. (2018), I estimated that a one-unit increase in the HYV adoption rate led to a 1.53 percentage point increase in the GDP per capita by 2000. I then combined this estimate with the

HYV adoption rate of each country to calculate the country-level direct effect. The figure shows that most countries benefited from HYV adoption, and the average effect across the sample countries was 42.7 percentage points by 2000.

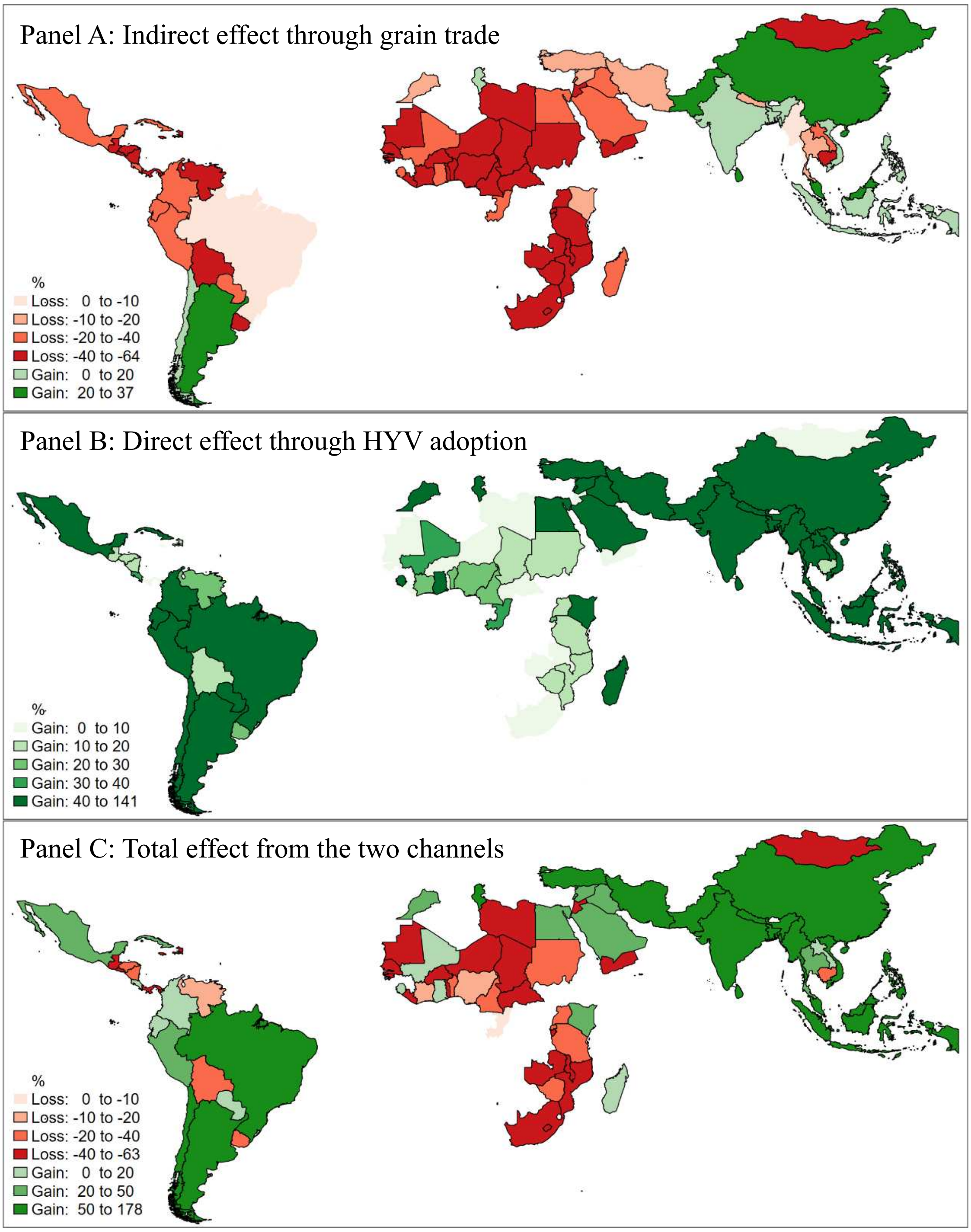

Figure 5. Impact of the GR on GDP per capita through two channels

Note: The indirect effect through grain trade (Panel A) is calculated based on the baseline 2SLS estimates reported in column 2 of Table 2. The direct effect through HYV adoption (Panel B) is calculated based on the 2SLS estimates from column 2 of Table D1. The total effect (Panel C) is calculated as the sum of direct and indirect effects.

Panel C presents the total effect, which is calculated as the sum of the direct and indirect effects from Panels A and B of the same figure. It shows that the GR increased the GDP per capita in 38 countries while reducing that in the remaining 40 countries. The average effect across the 78 countries was mildly positive (9.6 percentage points). Countries that experienced the largest loss in GDP per capita were mainly from Africa, whereas countries that gained the most were mainly from Asia. Sixteen African countries experienced a more than 40 percentage point loss in GDP per capita by 2000 (Mozambique, Chad, Guinea, Zambia, Senegal, South Africa, Burkina Faso, Togo, Malawi, Liberia, Mauritania, Libya, Central African Republic, Niger, Burundi, and Republic of the Congo). In contrast, the GR more than doubled the GDP per capita in eight Asian countries (China, Malaysia, Sri Lanka, Pakistan, Viet Nam, India, Philippines, and Indonesia) during the same period. However, not just African countries experienced a dramatic loss from the GR. Countries that experienced a more than 40 percentage point loss were also from the Caribbean (Haiti, Guatemala, El Salvador, Panama, and Jamaica), Middle East (Yemen and Jordan), and Asia (Mongolia).

Finally, I illustrate the extent to which the observed income divergence between developing countries could be explained by the estimated effects of the GR presented in Figure 5. To do so, I classify the sample countries into two groups based on whether the total effect of the GR on their 2000 GDP per capita was positive (38 countries) or negative (40 countries). I then compared the actual GDP per capita of the two groups with the corresponding counterfactual GDP per capita that eliminates the total effect of the GR.[26] Figure 6 presents the actual and counterfactual GDP per capita for the two groups of countries from 1960 to 2000. The actual difference in GDP per capita between these two groups of countries almost tripled from 1267 US$ in 1960 to 3475 US$ in 2000. In sharp contrast, when the total effect of the GR was excluded, these two groups roughly paralleled in GDP per capita from 1960 to 1980 and then converged. Therefore, the income divergence observed between these two groups of developing countries from 1960 to 2000 can be mostly explained by the GR.

[26] The counterfactual GDP per capita (income for short) for each group in a given year, such as 1990, is calculated in three steps: first, a country's 1960 income is multiplied with the estimated total percentage-point effect of the GR on the country's income by 1990 to obtain the changes in income from 1960 to 1990 that were caused by the GR; second, I subtracted the calculated GR's effect in step 1 from the observed 1990 income to obtain the counterfactual income in 1990 for each country; finally, I calculated the (simple) average counterfactual income across countries from each group.

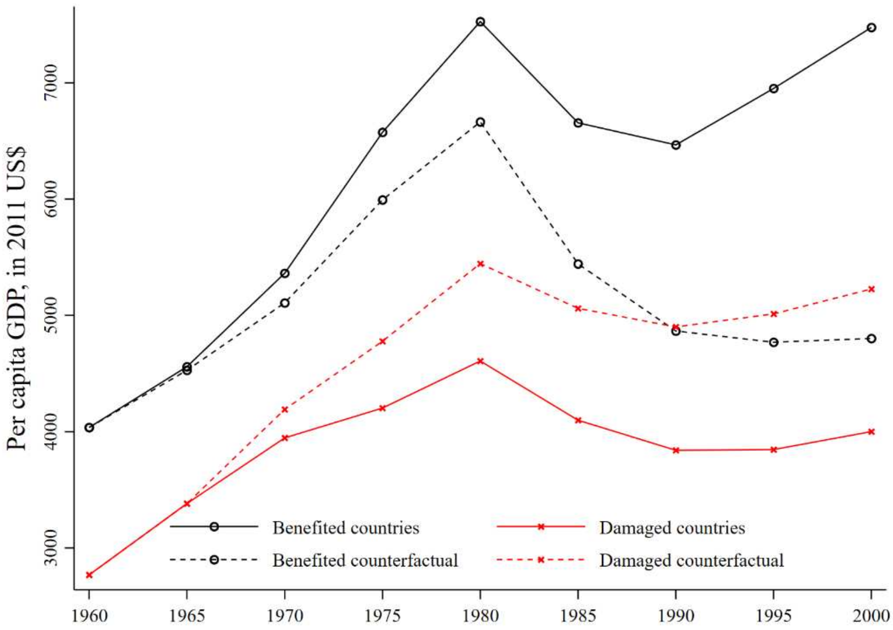

Figure 6. Explanatory power of the GR on the income divergence

Note: The figure classifies the 78 sample countries into two groups based on whether the total effect of the GR on their 2000 GDP per capita was positive (38 countries) or negative (40 countries). The solid lines represent the observed GDP per capita, and the dashed lines represent the counterfactual GDP per capita that eliminates the estimated effect of the GR (See Footnote 26 for details).

7. Concluding Remarks

A longstanding question in economics is why some countries are so much richer than others. A natural starting point to answer this question is to examine the origin of the historical income divergence. The two largest income divergences in modern history coincided in timing and region with the two most significant agricultural revolutions, suggesting that the cross-country asymmetric agricultural growth could be the origin of income divergence. This study showed that large subsets of developing countries shared nearly identical growth trends for centuries dramatically diverged in income per capita since the GR. Depending on data from 78 developing countries, this study shows that the GR could explain most of the income divergence across developing countries since the 1960s. It also shows that the GR led countries more suitable for cultivating GR crops to experience faster growth in manufacturing, larger increases in education, more accumulation of physical capital, and slower growth of population. The effects on these income determinants explained why differences in agricultural productivity from the GR could lead to such a large income divergence.

Beyond the conventional wisdom that domestic agricultural growth promotes domestic income growth, this study shows that a disadvantage in agriculture (relative to foreign countries) hinders the growth of developing countries via international trade. It shows that countries that gained comparative advantage in agriculture from the GR tend to also gain comparative advantage in manufacturing and, therefore, lead other developing countries to specialize in unpromising extractive industries. This finding provides an explanation for the widely documented "growth puzzle" that many developing countries stagnated during the 1980s and 1990s, despite the adoption of policy reforms (e.g., Bairoch 1995, Stiglitz 2002).[27] This finding also explains why the second income divergence since the 1960s was much more dramatic than the first income divergence since the early 19th century: the far more integrated global environment enlarged the impact of relative agricultural productivity growth on income divergence via promoting international trade.[28]

I would like to conclude this article by highlighting its major policy implication: developing countries generally cannot bypass an agricultural revolution to successfully launch their economic transformations, even in an integrated global environment with declining food prices. This study shows that for developing countries disadvantaged in agriculture, declining food prices in the world market are detrimental, instead of beneficial, for their transition to industry and long-run growth. Moreover, it also suggests that countries generally cannot avoid the detrimental effect of disadvantage in agriculture by protecting their agriculture from foreign trade because the detrimental effect works not only through agricultural trade but also through the trade of non-agricultural products. Because unsuitability for cultivating GR crops is a major cause of the stagnant growth in a large subset of developing countries over the past decades, research programs focusing on improving agricultural productivity for these countries may be effective in helping them catch up in economic growth.

[27] Existing studies explained the stagnant growth by political instability, dysfunctional institutions, low schooling, and insufficient infrastructure (Easterly and Levine 1997, Temple and Johnson 1998, Collier and Gunning 1999, Acemoglu et al. 2001, Brunnschweiler and Bulte 2008, Huillery 2009). This study shows that countries that experienced stagnant growth or recessions during this period are mainly those with a relatively low adoption rate of GR crops (Figure B4).

[28] Another important reason is that the GR for developing countries is built on the scientific advances already made in the developed world.

References

Acemoglu, Daron. 2009. *Introduction to modern economic growth*. Princeton, NJ: Princeton University Press.

Acemoglu, Daron, Simon Johnson, and James Alan Robinson. 2005. "Institutions as the fundamental cause of long-run growth." In *Handbook of Economic Growth*, edited by Philippe Aghion and Steven Durlauf. Amsterdam: North-Holland.

Acemoglu, Daron, Simon Johnson, and James A Robinson. 2001. "The colonial origins of comparative development: An empirical investigation." *The American Economic Review* 91 (5):1369-1401.

Allen, Robert C. 2011. *Global economic history: a very short introduction*. Vol. 282. Oxford, England: Oxford University Press.

Andersen, Thomas Barnebeck, Peter Sandholt Jensen, and Christian Volmar Skovsgaard. 2016. "The heavy plow and the agricultural revolution in Medieval Europe." *Journal of Development Economics* 118:133-149.

Bairoch, Paul. 1995. *Economics and world history: Myths and paradoxes*. Chicago, United States: University of Chicago Press.

Baldwin, Richard E, Philippe Martin, and Gianmarco IP Ottaviano. 2001. "Global income divergence, trade, and industrialization: The geography of growth take-offs." *Journal of Economic Growth* 6 (1):5-37.

Barro, Robert J, and Jong Wha Lee. 2013. "A new data set of educational attainment in the world, 1950–2010." *Journal of Development Economics* 104:184-198.

Barro, Robert J, and Xavier Sala-i-Martin. 2004. *Economic Growth*. The second ed. Cambridge, Massachusetts: The MIT Press.

Becker, Gary S, and H Gregg Lewis. 1973. "On the interaction between the quantity and quality of children." *Journal of Political Economy* 81 (2, Part 2):S279-S288.

Becker, Gary S, Kevin M Murphy, and Robert Tamura. 1990. "Human capital, fertility, and economie growth." *Journal of Political Economy* 98 (5):S12-S37.

Ben-David, Dan. 1993. "Equalizing exchange: Trade liberalization and income convergence." *The Quarterly Journal of Economics* 108 (3):653-679.

Brunnschweiler, Christa N., and Erwin H. Bulte. 2008. "Linking natural resources to slow growth and more conflict." *Science* 320 (5876):616-617.

Bustos, Paula, Bruno Caprettini, and Jacopo Ponticelli. 2016. "Agricultural productivity and structural transformation: Evidence from Brazil." *The American Economic Review* 106 (6):1320-65.

Cameron, A. Colin, and K. Trivedi Pravin. 2010. *Microeconometrics using Stata, revised edition*, *Stata Press books*: StataCorp LP.

Carillo, Mario F. 2021. "Agricultural policy and long-run development: Evidence from Mussolini's battle for grain." *The Economic Journal* 131 (634):566-597.

Chen, Shuo, and James Kai-sing Kung. 2016. "Of maize and men: The effect of a New World crop on population and economic growth in China." *Journal of Economic Growth* 21 (1):71-99.

Collier, Paul, and Jan Willem Gunning. 1999. "Explaining African economic performance." *Journal of Economic Literature* 37 (1):64-111.

Conway, Gordon. 2012. *One billion hungry: Can we feed the world?* New York, United States: Cornell University Press.

Dall Schmidt, Torben, Peter Sandholt Jensen, and Amber Naz. 2018. "Agricultural productivity and economic development: the contribution of clover to structural transformation in Denmark." *Journal of Economic Growth* 23 (4):387-426.

Easterly, William, and Ross Levine. 1997. "Africa's growth tragedy: Policies and ethnic divisions." *The Quarterly Journal of Economics* 112 (4):1203-1250.

Evenson, Robert E. 2005. "Besting Malthus: the green revolution." *Proceedings of the American Philosophical Society* 149 (4):469-486.

Evenson, Robert E, and Douglas Gollin. 2003a. "Assessing the impact of the Green Revolution, 1960 to 2000." *Science* 300 (5620):758-762.

Evenson, Robert E, and Douglas Gollin. 2003b. *Crop variety improvement and its effect on productivity: The impact of international agricultural research*. Edited by Robert E Evenson and Douglas Gollin. Cambridge, MA: CABI Publishing.

FAO. 2000. *Trade liberalization and food security: Conceptual links*, *Trade Reform and Food Security*. Rome: FAO Document.

Foster, Andrew D, and Mark R Rosenzweig. 1996. "Technical change and human-capital returns and investments: evidence from the green revolution." *The American economic review*:931-953.

Frankel, Jeffrey, and David Romer. 1999. "Does trade cause growth?" *The American Economic Review* 89 (3):379.

Galor, Oded, and Andrew Mountford. 2006. "Trade and the great divergence: the family connection." *The American Economic Review* 96 (2):299-303.

Galor, Oded, and Andrew Mountford. 2008. "Trading population for productivity: theory and evidence." *The Review of Economic Studies* 75 (4):1143-1179.

Galor, Oded, and David N. Weil. 2000. "Population, technology, and growth: From Malthusian stagnation to the demographic transition and beyond." *The American Economic Review* 90 (4):806-828.

Gollin, Douglas, Hansen Casper Worm, and Wingender Asger. 2018. *Two blades of grass: The impact of the Green Revolution*, *NBER Working Papers 24744*: National Bureau of Economic Research.

Gollin, Douglas, Stephen Parente, and Richard Rogerson. 2002. "The role of agriculture in development." *The American Economic Review* 92 (2):160-164.

Grossman, Gene M, and Elhanan Helpman. 1991. "Quality ladders in the theory of growth." *The Review of Economic Studies* 58 (1):43-61.

Hart, Gillian. 1998. "Regional linkages in the era of liberalization: A critique of the new agrarian optimism." *Development and Change* 29 (1):27-54.

Hazell, Peter BR. 2009. *The Asian green revolution*. Washington, DC: International Food Policy Research Institute.

Hazell, Peter BR. 2010. *Proven successes in agricultural development*. Edited by D Spielman and R Pandya-Lorch. Washington, DC: International Food Policy Research Institute.

Huillery, Elise. 2009. "History matters: The long-term impact of colonial public investments in French West Africa." *American Economic Journal: Applied Economics* 1 (2):176-215.

Jones, Eric. 1981. *The European miracle: environments, economies and geopolitics in the history of Europe and Asia*. Cambridge, UK: Cambridge University Press.

Jones, Peter M. 2016. *Agricultural enlightenment: knowledge, technology, and nature, 1750-1840*. Oxford, England: Oxford University Press.

Kopsidis, Michael, and Nikolaus Wolf. 2012. "Agricultural productivity across Prussia during the Industrial Revolution: A Thünen perspective." *The Journal of Economic History*:634-670.

Krugman, Paul, and Anthony J Venables. 1995. "Globalization and the inequality of nations." *The*

Quarterly Journal of Economics 110 (4):857-880.

Laitner, John. 2000. "Structural change and economic growth." *The Review of Economic Studies* 67 (3):545-561.

Matsuyama, Kiminori. 1992. "Agricultural productivity, comparative advantage, and economic growth." *Journal of Economic Theory* 58 (2):317-334.

Max, Roser, and Ritchie Hannah. 2019. Food prices. Published online at OurWorldInData.org.

Mayer, Thierry, and Soledad Zignago. 2011. "Notes on CEPII's distances measures: The GeoDist database." *CEPII Working Paper 2011-25*.

McCalla, Alex F. 2001. What the developing countries want from the WTO. *Estey Journal of International Law and Trade Policy* 02 (1): 165-177. Accessed 2001.

Mokyr, Joel. 2001. *The gifts of Athena: Historical origins of the knowledge economy*. Princeton, NJ: Princeton University Press.

Mokyr, Joel. 2011. *The enlightened economy: Britain and the industrial revolution, 1700-1850*. London, England: Penguin UK.

Nunn, Nathan, and Nancy Qian. 2011. "The potato's contribution to population and urbanization: Evidence from a historical experiment." *The Quarterly Journal of Economics* 126 (2):593-650.

Overton, Mark. 1996. *Agricultural revolution in England: the transformation of the agrarian economy 1500-1850*. Cambridge, England: Cambridge University Press.

Pingali, Prabhu L. 2012. "Green Revolution: Impacts, limits, and the path ahead." *Proceedings of the National Academy of Sciences* 109 (31):12302-12308.

Pomeranz, Kenneth. 2000. *The Great Divergence: China, Europe, and the Making of the Modern World Economy*: Princeton University Press.

Renkow, Mitch, and Derek Byerlee. 2010. "The impacts of CGIAR research: A review of recent evidence." *Food Policy* 35 (5):391-402.

Restuccia, Diego, Dennis Tao Yang, and Xiaodong Zhu. 2008. "Agriculture and aggregate productivity: A quantitative cross-country analysis." *Journal of Monetary Economics* 55 (2):234-250.

Shrout, P. E., and N. Bolger. 2002. "Mediation in experimental and nonexperimental studies: new procedures and recommendations." *Psychol Methods* 7 (4):422-45.

Stiglitz, J. 2002. *Globalization and its discontents*. New York and London: W.W. Norton.

Temple, Jonathan, and Paul A Johnson. 1998. "Social capability and economic growth." *The Quarterly Journal of Economics* 113 (3):965-990.

Vollrath, Dietrich. 2011. "The agricultural basis of comparative development." *Journal of Economic Growth* 16 (4):343-370.

Wooldridge, Jeffrey M. 2010. *Econometric analysis of cross section and panel data*. Cambridge, MA: MIT press.

World Bank. 2007. *World Bank assistance to agriculture in Sub-Saharan Africa: An IEG review.* Washington D.C.: World Bank.

Young, Alwyn. 1991. "Learning by doing and the dynamic effects of international trade." *The Quarterly Journal of Economics* 106 (2):369-405.

Online Appendix

A. Data Sources

This paper depends on data mainly obtained from the following six sources: (1) the GDP and population data from the Maddison Project Database 2018; (2) the HYV adoption rate data from Evenson and Gollin (2003b); (3) the grain trade data from the FAO Statistical Databases; (4) the data on agro-climatic suitability for cultivating crops from the Global Agro-Ecological Zone dataset computed by FAO; (5) the data on various control variables and trade of non-grain products from the World Development Indicators of the World Bank; and (6) the data on bilateral distances between countries from Mayer and Zignago (2011).

From these datasets, I constructed a sample of 78 developing countries in five-year intervals from 1960 to 2000 (according to the criteria detailed in Footnote 13). Note that grain trade data from the FAO Statistical Databases are not available before 1961. To match with the 5-year interval HYV adoption data starting from 1960, I used the grain trade in 1961 as an approximation of that in 1960. Table A1 lists the 78 sample countries. Table A2 presents the data source and definition of each of the 28 variables used in this study. Summary statistics are presented in various figures in the main text and Appendix B1.

Table A1. The Sample Countries

Argentina	Haiti	Nigeria
Bangladesh	Honduras	Pakistan
Benin	India	Panama
Bolivia	Indonesia	Paraguay
Brazil	Iran	Peru
Burkina Faso	Iraq	Philippines
Burundi	Jamaica	Rwanda
Cambodia	Jordan	Saudi Arabia
Cameroon	Kenya	Senegal
Central African Rep.	Laos	Sierra Leone
Chad	Lebanon	South Africa
Chile	Liberia	Sri Lanka
China	Libya	Sudan
Colombia	Madagascar	Syria
Congo, Dem. Rep.	Malawi	Tanzania
Congo, Rep.	Malaysia	Thailand
Costa Rica	Mali	Togo
Cuba	Mauritania	Tunisia
Cote D'ivoire	Mexico	Turkey
Dominican Rep.	Mongolia	Uganda
Ecuador	Morocco	Uruguay
Egypt	Mozambique	Venezuela
El Salvador	Myanmar	Viet Nam
Ghana	Nepal	Yemen
Guatemala	Nicaragua	Zambia
Guinea	Niger	Zimbabwe

Note: The table lists the 78 sample countries for which the data on HYV adoption and GDP per capita are available from 1960 to 2000 and the 1960 population was larger than 1 million.

Table A2. Definition and Data Sources of all Variables Used

Variable name	Definition	Sources
Key variables		
HYV adoption rate	Country-level yearly HYV adoption rates of the 10 major food crops.	A
Net grain imports	Yearly import values minus export values for the 10 major crops together in 2011 US$.	B
GDP	Real GDP in 2011 US$.	C
Population	Middle-year total population in thousands.	C
Agro-climatically attainable yield	The highest attainable yield under the local climatic conditions.	D
Crop harvested area	Country-level yearly harvested area of each crop in hectare (used when calculating the RDS).	B
Variables used in summary statistics or robustness tests		
Per hectare grain yield	The harvesting-area-weighted average (rice equivalent, see Appendix B1) yield of the 10 crops in tons.	B
Grain import-consumption ratio	The ratio of net import to domestic consumption of the 10 major food crops.	B
Bilateral distance	Bilateral distance between countries in 1000 km.	E
Net manufacture imports	The sum of the net import values of chemicals, basic manufactures, machinery and transport equipment, and miscellaneous manufactured goods.	F
Net raw material imports	The sum of the net import values of fuel, ores, metals, and agricultural products besides the 10 major crops.	F
Control variables		
The share of agriculture in GDP	The percentage of agriculture, forestry, and fishing value added in total GDP.	F
The crude birth rate	Annual number of births per 1,000 people.	F
Life expectancy	Life expectancy at birth.	F
Dependency ratio	Yearly percentage of working-age population.	F
Log capital formation per capita	Log capital formation per capita in 2011 US$.	F
Log inward FDI per capita	Log inward FDI per capita in 2011 US$.	F
Landlocked	Whether the country is landlocked, dummy.	E
Soil rooting condition	Country average farmland soil rooting condition index.	B
Soil nutrient index	Country average farmland soil nutrient index.	B
Precipitation	Annual total precipitation in mm.	D
Temperature	Annual mean temperature in degree centigrade.	D
Log 1960 GDP per capita	Log real GDP per capita in 1960 in 2011 US$.	C
Official language	The first official language of the country.	E
Colonizer	The most important colonizer that participated in long period and substantial governance.	E
Per hectare grain output	Per hectare output value of the 10 major crops in 2011 US$.	B
Urbanization	The percentage of the population in urban agglomerations with 500,000 or more inhabitants.	H
Years of schooling	Average years of schooling for population aged 25 and over.	G

Data sources: A. Evenson and Gollin (2003b)
B. FAO Statistical Databases.
C. Maddison Project Database 2018.
D. Global Agro-ecological Zone data, FAO.
E. Mayer and Zignago (2011)
F. World Development Indicators, the World Bank.
G. Barro and Lee (2013)
H. The UN World Urbanization Prospects (2018) database

B. Appendix for the GR's Effect on Trade

This appendix provides the summary statistics of the effects of GR on grain productivity, prices, and trade. It also details the construction of the predicted RDS. Finally, it provides falsification tests to show that the RDS has no effect on grain trade prior to the GR.

B1 Summary Statistics

Figure B1 presents the correlation between the adoption rate of HYVs in 2000 and the changes in the productivity of 10 major crops from 1965 to 2000 in 78 developing countries. To make the yields of the 10 crops comparable, I calculated their rice equivalents based on the calorie content. For example, 1 ton of potatoes has 763,353 calories, the same number of calories that are in 0.221 tons of rice because rice has 3439,348 calories per ton. As such, one ton of potatoes expressed in rice equivalents is 0.221 tons. The calorie content information was obtained from the nutritional composition table provided by the United Nation World Food Program.

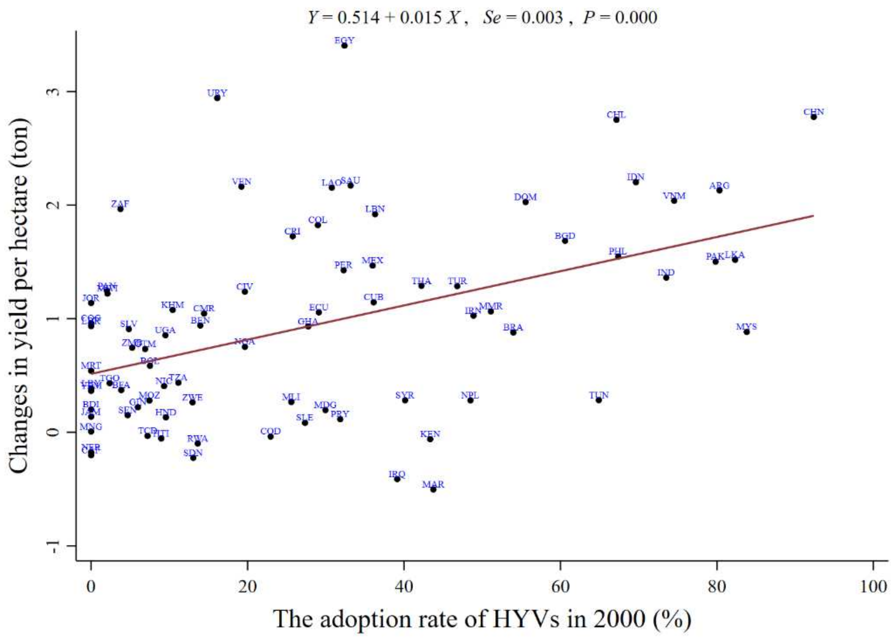

Figure B1. Correlation between the adoption rate of HYVs in 2000 and changes in the crop productivity from 1965 to 2000 in 78 developing countries

Notes: The country-level adoption rate of HYVs was calculated as the weighted-average across the 10 major food crops, using each crop's harvesting area as the weighting. The 10 major crops are wheat, rice, maize, barley, potatoes, millet, sorghum, cassava, dry beans, and groundnut. The yield per hectare is calculated as the *rice equivalent* (harvesting-area-weighted) average yield of the 10 crops. The data for HYV adoption rate and yield are derived from Evenson and Gollin (2003b) and the FAO Statistical Databases, respectively.

Figure B2 shows that the average price index for the three GR crops (rice, wheat, and maize) declined from 71.9 in 1960 to 18.5 in 2000. The price decline was not caused by the reduced food demand because (as shown in the same figure) the world population doubled from 3.02 billion to 6.12 billion during this period.

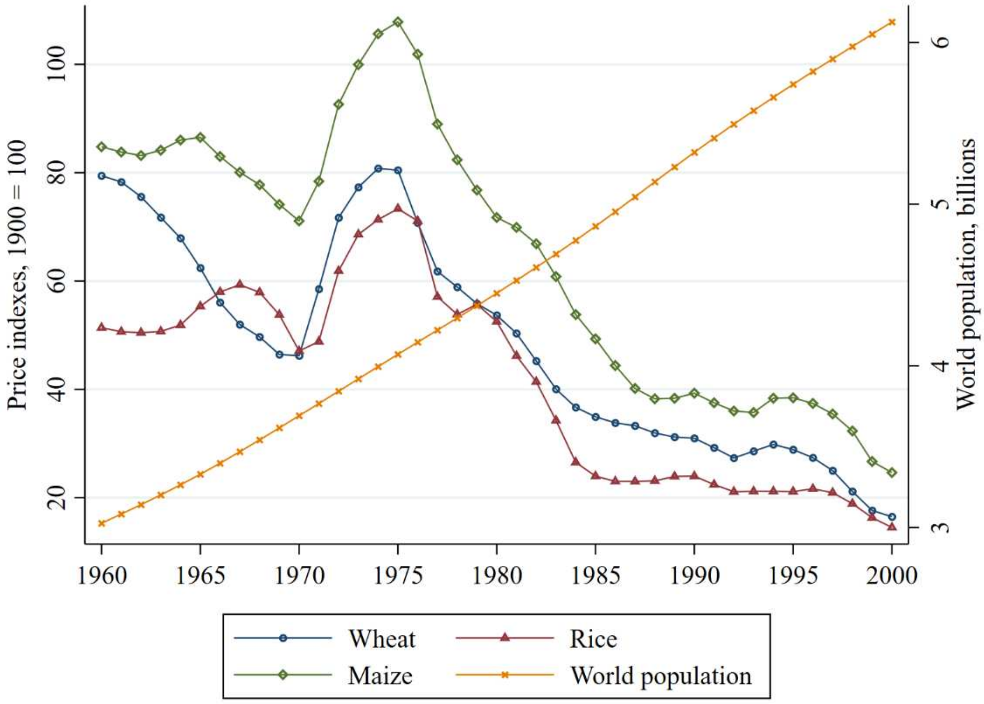

Figure B2. Real prices of three major staple crops and the world population

Data sources: Price indexes, Max and Hannah (2019); world population, the Maddison Project Database 2018.

Table B1 shows that the domestic prices of the GR corps in developing countries were highly correlated with the world prices, even for relatively closed countries. For each crop, I calculated the Pearson correlation coefficient (PCC) between the international price index and the domestic price (in international dollars) for each country during 2000–2010.[29] The table presents the average PCC for each category of countries indicated in the leftmost column. Panel A classifies the sample countries according to their import-consumption ratio for each crop. It shows a strong positive correlation between the domestic and world prices, even for countries with an import-consumption ratio lower than 5%. Similarly, Panel B classifies the sample countries according to their adoption rates of HYVs and also shows a strong positive correlation, even for countries most disadvantaged in adopting HYVs.

[29] Domestic crop prices prior to 2000 are unavailable for many developing countries. I also examined the correlation prior to 2000 for countries for which the data are available and found similar results.

Table B1. Correlation between international and domestic prices of major crops

	Averaged Pearson correlation coefficient		
	Rice	Wheat	Maize
A. Classified according to the import-consumption ratio			
Higher than 20%	0.82	0.70	0.73
	(0.22)	(0.20)	(0.31)
Between 5% and 20%	0.67	0.85	0.73
	(0.51)	(0.12)	(0.22)
Lower than 5%	0.76	0.65	0.69
	(0.24)	(0.05)	(0.09)
B. Classified according to the disadvantage in adopting HYVs			
All disadvantaged countries	0.75	0.74	0.72
	(0.35)	(0.18)	(0.26)
One-third most disadvantaged	0.73	0.77	0.75
	(0.48)	(0.12)	(0.20)
One-fifth most disadvantaged	0.77	0.82	0.73
	(0.39)	(0.11)	(0.28)

Note: The table presents the average Pearson correlation coefficient (PCC) between the international price index and the domestic price (in Int'l$) during 2000–2010 for each category of countries. The sample countries are 66 developing countries disadvantaged in adopting HYVs. A PCC of 0.5 or larger is usually thought to represent a strong correlation. The standard deviations are reported in parentheses.

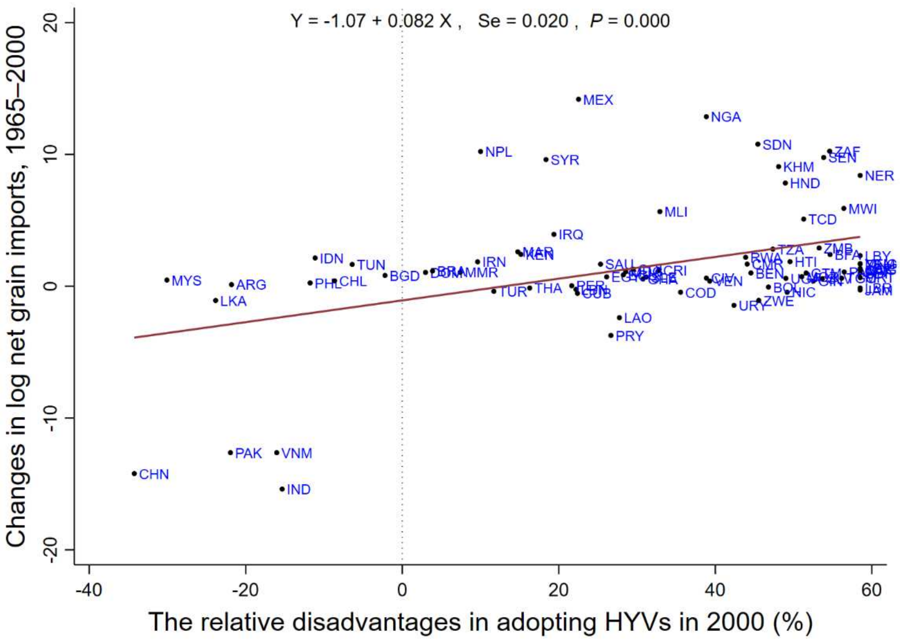

Figure B3. Correlation between the RDS in 2000 and the changes in the log net grain imports from 1965 to 2000

Figure B3 presents the significantly positive correlation between the RDS in 2000 and the changes in the log net grain imports from 1965 to 2000. A simple regression showed that a one-unit increase in the RDS corresponds to an 8.2 percentage point increase in grain imports, which is similar to the effect estimated by the fixed-effect panel model in Table 1. The figure also shows that all countries that experienced a large increase in the grain imports are GR-disadvantaged countries (with a positive RDS). For an average disadvantaged country, the *log* net grain imports increased by 2.5 from 1965 to 2000, which corresponds to a 1,118 percentage point increase in the net grain imports (i.e., $\exp(2.5)-1=11.18$). The largest increase in the net grain exports (i.e., decline in net grain imports) occurred in the four Asian countries advantaged in adopting HYVs: China, India, Pakistan, and Vietnam.

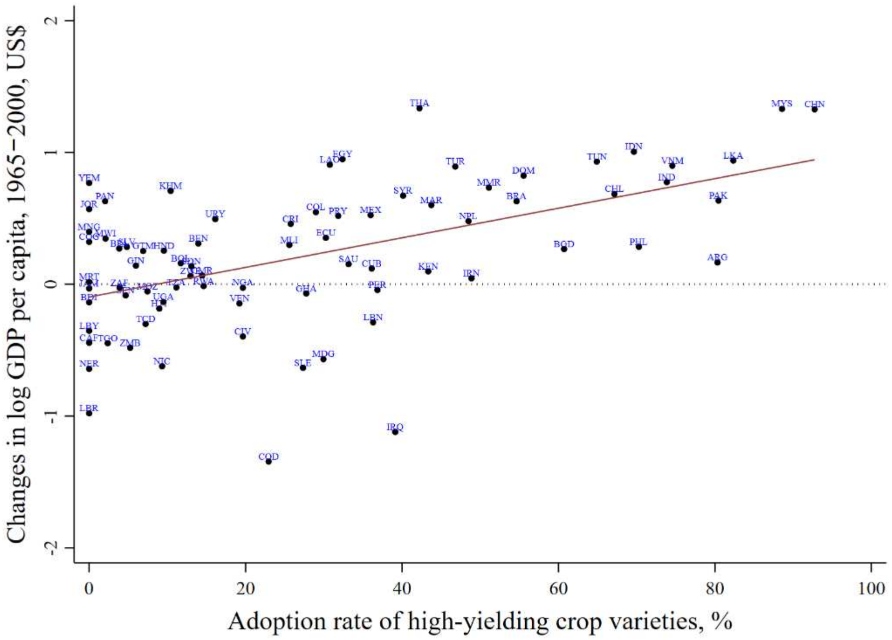

Figure B4. Correlation between changes in the log GDP per capita from 1965 to 2000 and the adoption rate of HYVs in 2000

Notes: The figure contains 78 developing countries where the data on HYV adoption rates are available. The data are derived from Evenson and Gollin (2003b) and the Maddison Project Database 2018.

Figure B4 presents a strongly positive correlation between changes in the log GDP per capita from 1965 to 2000 and the adoption rate of HYVs in 2000 (the adoption rate in 1965 was virtually zero) for 78 developing countries. Strikingly, 27 countries with relatively low HYV adoption rates experienced significant declines in GDP per capita over this period.

B2 The Predicted RDS

To address the concern that the RDS could be endogenous, I constructed an excluded IV for the RDS based on two sources of plausibly exogenous variation—the cross-sectional variation in the agro-climatic suitability for growing HYVs and the differentiated timing of the development of HYVs for different crops. A country's agro-climatic conditions should not be affected by the time-varying determinants of economic outcomes, and the timing of the development of HYVs is exogenous to individual developing countries (Conway 2012).

The data on agro-climatic suitability for growing HYVs are derived from the Global Agro-Ecological Zone (GAEZ) dataset computed by FAO. The GAEZ data provide each major crop's agro-climatically attainable yield, which is the highest attainable yield under the local climatic conditions and is estimated using complex biological models.[30] The attainable yield varies across locations and crops. The cost of purchasing HYV seeds is independent of climate; thus, the net return of adopting them increases with the agro-climatically attainable yield. Regions with higher attainable HYV yields should have higher adoption rates. I used the attainable yield under the high input level (i.e., full application of synthetic fertilizer, irrigation, mechanization, and HYVs) that corresponds to modern farming techniques.

The IV for the RDS is constructed in three steps. The first step is to estimate the following:

$$HYV_{it}^{j} = v_i + \tau_t + \sum_{k=1965}^{2000} \gamma_k^j \, potential_i^j \times year_t^k + u_{it}^j \quad , \tag{6}$$

where HYV_{it}^{j} is the real HYV adoption rate of crop j in country i and year t, and $potential_i^j$ is the average agro-climatically attainable yield of crop j across all land suitable for agriculture in country i. To capture the fact that the HYVs of some crops were developed later than others, the $potential_i^j$ is interacted with a full set of time dummies, $year_t^k$. The regression also includes year and country-fixed effects, and u_{it}^j is the error term.

The second step is to predict the adoption rate of each crop based on estimates of equation (6) and, then, to use the crop-level predicted value to calculate the country-

[30] I refer the reader to the FAO GAEZ webpage (http://www.fao.org/nr/gaez/en/) for technical details.

level predicted adoption rate according to the following:

$$pHYV_{it} = \frac{\sum_{j=1}^{J} HYV_{it}^{j} \times Area_{i1960}^{j}}{\sum_{j=1}^{J} Area_{i1960}^{j}} \quad ,$$

where HYV_{it}^{j} is the predicted HYV adoption rate of crop j in country i and year t, and $Area_{i1960}^{j}$ is the 1960 harvested area of crop j in country i.

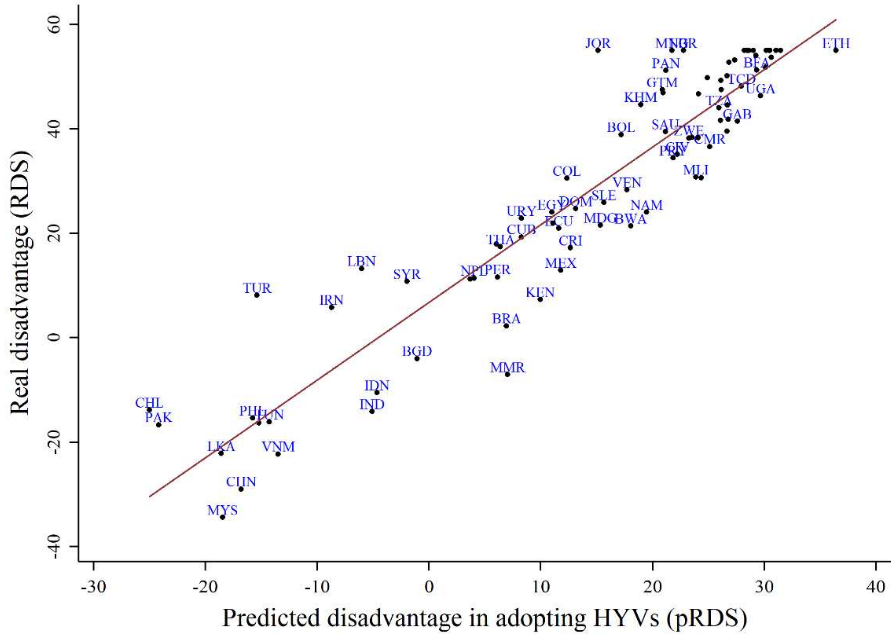

Figure B5. Correlation between the predicted and the real disadvantage of adopting HYVs in 2000

The final step is to use the country-level predicted adoption rate to calculate the predicted RDS:

$$pRDS_{it} = \overline{pHYV}_{t} - pHYV_{it} \quad ,$$

where $\overline{pHYV}_{t}$ is the average predicted adoption rate across all sample countries calculated according to the following:

$$\overline{pHYV}_{t} = \frac{\sum_{i=1}^{I} pHYV_{it} \times TotalArea_{i1960}}{\sum_{i=1}^{I} TotalArea_{i1960}} \quad ,$$

where $TotalArea_{i1960}$ is the 1960 total harvested area of the 10 crops in country i. As presented in Figure B5, the predicted RDS is strongly correlated with the observed RDS in 2000. The correlations are similarly strong in other sample years after 1970.

B3 Falsification Tests for the Effect of RDS on Grain Imports

This appendix provides the falsification tests for the effect of RDS on grain imports. I estimated a flexible version of model (1) that replaces the RDS by the interactions between the 1965–2000 average predicted RDS ($\overline{pRDS}_i$) and a full set of year dummies ($year_t^k$):

$$\ln Imp_{it} = \nu_i + \tau_t + \sum_{k=1962}^{2016} \alpha_k \overline{pRDS}_i \times year_t^k + Z_{it}\lambda + \varepsilon_{it} \quad . \tag{7}$$

Because continuous annual data on net grain imports are available from 1961 to 2016, the flexible model could estimate the effect of the average predicted RDS on grain imports in each year starting from 1961. If the predicted RDS captures only the effect of the GR, but not the effect of the preexisting differential trends across countries, the flexible model should find that the average predicted RDS had no effect on the grain imports prior to the GR.

As presented in Figure B6, the estimation indeed finds that the average predicted RDS had no effect on the grain imports prior to 1965, suggesting that no endogeneity bias from preexisting differential trends. In addition, the figure shows that the effect of the predicted RDS significantly increased shortly after 1965 and became significantly positive later on. This finding is consistent with the main estimate that higher RDS leads to more grain imports.

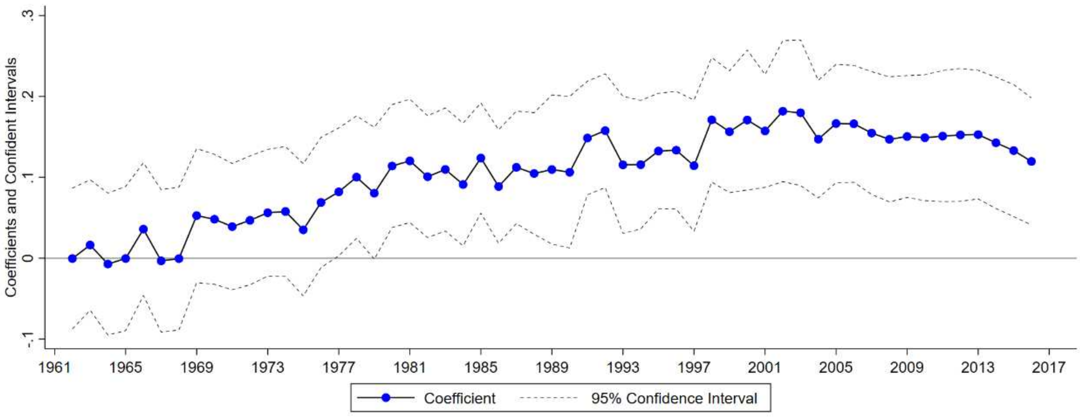

Figure B6. Flexible estimates of the effect of predicted RDS on grain imports

Note: Each dot on the solid line is a point estimate of a_ks from model (7), and the broken lines indicate the corresponding 95% confidence intervals.

C. Appendix for the Effect of the GR on Income

This appendix details the construction of the distance IV, provides additional robustness tests for the effect of grain imports on the GDP per capita, and presents the estimated effect of the GR-induced trade of manufactures and raw materials on GDP per capita.

C1 The Distance IV

The bilateral distance between countries has been widely employed as the IV for trade value, based on the assumption that the geographical distance affects a country's economic outcomes only through trade (e.g., Frankel and Romer 1999). As a robustness check, I constructed an alternative IV for grain imports using the bilateral distances to major grain-exporting countries.

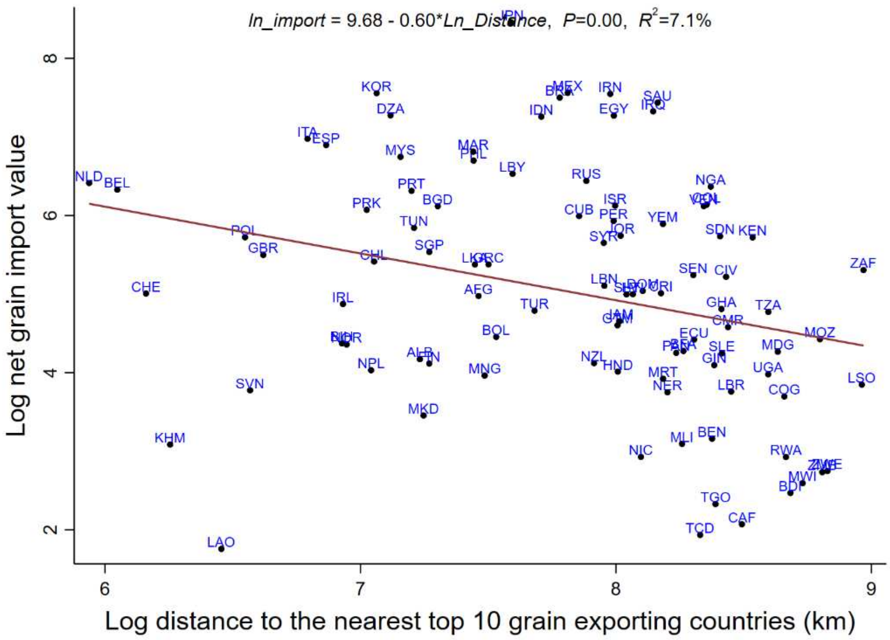

Figure C1. Correlation between the net grain import values and the distance to the nearest top 10 net exporting countries in 2000

Note: This figure contains only the net grain-importing countries in 2000. Similar correlations were found when using data from other sample years.

The distance IV is constructed using the bilateral distances (in terms of market access) calculated by Mayer and Zignago (2011).[31] In the construction, I first identify the 10 countries with the largest net export values of the 10 major food crops in each

[31] The bilateral distance between two countries is calculated using the distances between the two countries' biggest cities. See http://www.cepii.fr/cepii/en for more details.

year. The top exporting countries are chosen from all the countries in the world and not only from the developing countries examined in this article. I then use each sample country's bilateral distance to the *nearest* top 10 net exporting country as the IV. Note that the distance IV is time-varying partly because of the dramatic changes in the relative agricultural productivity across countries caused by the GR. As presented in Figure C1, the distance IV is strongly (p-value = 0.00) and negatively correlated with the net grain import values. I also constructed the bilateral distances to the nearest top 5 or 15 net grain-exporting countries in the same way and obtained similar results.

C2 Additional Robustness Checks

This appendix provides six groups of additional robustness checks for the baseline 2SLS estimation presented in column 2 of Table 2. Each of the robustness checks had the same model setting as the baseline estimation, except for the one specified in each check. All estimation results are presented in Table C1.

The per capita measure of grain imports: Column 1 uses the log net *per capita* grain imports (instead of the log net *total* grain imports) as the key explanatory variable. The main analysis does not use the per capita measure because changes in the per capita grain imports not only reflect the effect of the GR-caused grain imports but also reflect the effect of population growth. The estimation results suggest that higher *per capita* grain imports also reduce GDP per capita, and the marginal effect is much larger.

An alternative measure of the relative disadvantage: Column 2 uses the standardized RDS as the instrument variable, which is calculated as the RDS divided by its standard deviation. The normalization transforms the RDS from an interval measurement to a ratio measurement. Intuitively, the interval measurement (i.e., the RDS) is more relevant than the ratio measurement (i.e., the normalized RDS) when evaluating the relative disadvantage of a country in adopting HYVs. Nevertheless, when using the normalized RDS as the IV, the estimated coefficient is identical to the baseline estimate.

Robust to outliers: Columns 3 and 4 exclude sample countries that had very low or very high grain imports. A potential concern of the baseline estimation is that if the estimated effect is mainly driven by countries with extremely low or extremely high grain imports, we cannot arrive at a general conclusion that the GR-caused grain imports are detrimental. Because it is difficult to define the extreme values of grain imports, I simply excluded countries where the 2000 import-consumption ratio of the 10 major crops ranked below the bottom 10% (column 3) or above the top 10% (column 4). Excluding these potential extreme values does not alter the estimated effect. I also employed the threshold ranking values of 5% and 15% and obtained quite comparable results.

Robust to country-specific time trends: Columns 5 and 6 additionally control for country-specific linear and quadratic time trends, respectively. These robustness checks address the concern that the estimated effect may be driven by the omitted time trends. The robustness checks relieve this concern by finding estimates identical to the baseline estimate.

Robust to clustering methods: Columns 7 and 8 cluster the error terms at the country level and year level, respectively. The baseline estimation clusters the error terms at the region-year level to address the potential bias of the standard error due to the serial correlation over years or spatial correlation between countries within a region. These two robustness checks show that clustering the error terms at the country level (which addresses only series correlation) or year level (which addresses only spatial correlation) does not significantly alter the estimated standard error.

Sectoral effects of grain imports: Columns 9–11 estimate the baseline model by using the log per capita output in agriculture, manufacturing, and service industries as the dependent variable, respectively. These robustness checks can be used to verify the prediction that grain imports impact sectors beyond agriculture. However, because the data on sectoral population (or employment) are not available over most of the sample periods (generally unavailable until 1991), I had to calculate the sectoral *per capita* output as the ratio of the sectoral total GDP to the *national* total population. Because grain imports could lead to labor reallocation, the sectoral estimates may be overestimated or underestimated due to the lack of data on sectoral employment. The sectoral estimation shows a significantly negative effect of grain imports in each sector, with the largest marginal damage observed in manufacturing.

Table C1. Additional robustness checks of the baseline 2SLS estimate of Table 2

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Log net grain imports			-0.14***	-0.14***	-0.14***	-0.14***	-0.14***	-0.14***	-0.09***	-0.14***	-0.10***
(IV = RDS)			(0.03)	(0.02)	(0.02)	(0.02)	(0.05)	(0.02)	(0.01)	(0.03)	(0.02)
Log net per capita grain imports	-0.89***										
(IV = RDS)	(0.28)										
Log net grain imports		-0.14***									
(IV = Standardized RDS)		(0.05)									
Excluding the bottom 10% countries			Yes								
Excluding the top 10% countries				Yes							
Linear country-specific time trends					Yes						
Quadratic country-specific time trends						Yes					
Clustered by country							Yes				
Clustered by year								Yes			
Log per capita agriculture output									Yes		
Log per capita manufacturing output										Yes	
Log per capita service industry output											Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F statistics	9.39	13.0	28.2	38.4	34.0	34.0	11.9	161.4	34.2	30.9	37.5
Observations	702	702	631	632	702	702	702	702	684	657	657
R-squared	0.379	0.878	0.842	0.805	0.841	0.841	0.841	0.841	0.661	0.869	0.915

Notes: All columns have the same model setting as the baseline estimation (column 2 of Table 2), except for the one specified in each column. The first-stage F-statistic reported are the Kleibergen-Paap Wald F-statistic. If not specified, the standard errors (in parentheses) are clustered at the region-year level. The significance levels are *** p < 0.01, ** p < 0.05, * p < 0.1.

C3 The Effect of The GR-induced Trade of Other Products

This appendix examines the effect of the GR-induced trade of manufactures and raw materials on GDP per capita. This can be done by estimating a modified version of model (2) that replaces the key explanatory variable (i.e., net grain imports) by the net imports of manufactures or raw materials. The estimation results reported in Table C2 confirm the predictions that manufacture imports and raw material exports reduced the GDP per capita in the GR-disadvantaged countries. Specifically, the 2SLS estimate reported in column 2 indicates that a 1 percentage point increase in the net import of manufactures reduces the GDP per capita by 0.3 percentage points. The 2SLS estimate reported in column 7 indicates that a 1 percentage point increase in the net *export* of raw materials reduces the GDP per capita by 0.17 percentage points. The remaining columns in Table C2 contain the robustness checks. The OLS estimates reported in columns 1 and 6 are substantially smaller, highlighting the importance of addressing the endogeneity bias. Columns 3–5 and columns 8-10 show that comparable effects can be estimated when including various control variables or using the predicted RDS as the IV. Note that the estimated marginal effects in Table C2 are not comparable to those in Table 2 due to the difference in the study sample. As mentioned before, trade data on manufactures and raw materials in early years (prior to 1991) are unavailable for many developing countries. Thus, the sample size in Table C2 is approximately 40% smaller than that in Table 2. Therefore, the estimates in Table C2 reflect more the effect in more recent years and for countries where the early data are available.

Table C2. The effect of the imports of manufactures and raw materials on GDP per capita

Dependent variable: log real GDP per capita	(1) OLS	(2) 2SLS	(3) 2SLS	(4) 2SLS	(5) 2SLS	(6) OLS	(7) 2SLS	(8) 2SLS	(9) 2SLS	(10) 2SLS
Log net manufacture imports	-0.06***	-0.30***	-0.27***	-0.21***	-0.17***					
	(0.01)	(0.07)	(0.05)	(0.05)	(0.03)					
Log net raw material imports						0.02	0.17***	0.19***	0.14***	0.20***
						(0.01)	(0.03)	(0.04)	(0.03)	(0.05)
IV	No IV	RDS	RDS	RDS	pRDS	No IV	RDS	RDS	RDS	pRDS
Four time-invariant controls * year dummies			Yes		Yes			Yes		Yes
Eight time-varying control variables				Yes					Yes	
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F statistics		16.3	23.3	14.4	52.8		16.2	13.9	18.4	15.3
Observations	402	402	399	359	399	374	374	371	339	371
R-squared	0.953	0.877	0.908	0.924	0.944	0.947	0.865	0.865	0.910	0.853

Notes: This table reports the estimates of modified versions of model (2) that use the log net manufacture imports or log net raw material imports as the key explanatory variables. The first-stage F-statistic reported is the Kleibergen-Paap Wald F-statistic. The standard errors (in parentheses) are clustered at the region-year level. Significance levels are *** p < 0.01, ** p < 0.05, * p < 0.1.

D. The Direct Effect of HYV Adoption

This appendix examines the direct effect of the GR on GDP per capita by replicating the main estimation of Gollin et al. (2018), which can be rewritten as follows:

$$\ln y_{it} = \nu_i + \tau_t + \eta_1 HYV_{it} + \mu_{it} \quad (8)$$

where all variables are as defined in this article. I estimate equation (8) using the dataset of this article, which is similar to the dataset of Gollin et al. (2018).[32] The estimation results are reported in Table D1. To facilitate the comparison, Table D1 adopted the same format as Table 3 of Gollin et al. (2018), which I copied to Panel B of Table D1. Specifically, column 1 presents the OLS estimate; column 2 presents the 2SLS estimate, where the HYV is instrumented by the predicted HYV (see Appendix B2); and column 3 uses the predicted HYV instead of HYV for the OLS estimation. In Panel A, the 2SLS estimate suggests that a 1% higher HYV adoption rate increases GDP per capita by 1.53 percentage points, which is very close to the 2SLS estimate of Gollin et al. (2018) presented in Panel B.

Table D1. The effect of the HYV adoption rate on the GDP per capita

	Dependent variable: log GDP per capita		
	(1)	(2)	(3)
	OLS	2SLS	Reduced form
Panel A: Estimates of equation (8) using the dataset of this article			
Actual HYV adoption rate	1.05***	1.53***	
	(0.20)	(0.24)	
Predicted HYV adoption rate			1.54**
			(0.63)
Country-fixed effect	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
Observations	702	702	702
Countries	78	78	78
R-squared	0.944	0.942	0.938
Panel B: Estimates reported in Table 3 of Gollin et al. (2018)			
Actual HYV adoption	0.99***	1.48***	
	(0.18)	(0.40)	
Predicted HYV adoption			1.80***
			(0.54)

Notes: Standard errors clustered at the country-level are listed in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

[32] While this study uses 5-year interval data, their paper used 10-year interval data. In addition, a sample country of this study (Jordan) was not included in their study, while two of their sample countries (Angola and Algeria) were excluded from this study due to missing values of GDP.