The diffusion of genetic resources and yield gaps in the developing world

By Nicholas Tyack*

The Green Revolution was a major public sector investment in the development of improved crop varieties that led to the uptake in many countries of high-yielding modern varieties (along with other inputs such as fertilizer). This analysis aims to examine how these investments in the development and dissemination of improved crop varieties contributed (or did not contribute) to productivity growth and yield convergence for a number of crops across the developing world. I further investigate the role played by country-level investments in agricultural research and development, the protection of intellectual property rights, and hybrid technology in aiding or restricting the diffusion of innovation. To empirically analyze these questions, I use a cross-country database on agricultural productivity, crop yields and modern variety adoption rates including 77 developing countries between 1960 and 2005. I employ dynamic panel data methods (namely the two-step system GMM estimator) to address endogeneity concerns, and include a number of variables to disentangle other drivers of productivity growth such as increased use of inputs per hectare of fertilizers, machinery, livestock, and labor.

JEL: O31, O32, O33, O34, Q12, Q16
Keywords: Technology diffusion; genetic resources; agricultural productivity; Green Revolution; intellectual property; yield gap

* Nicholas Tyack: Department of International Economics, The Graduate Institute, Geneva (IHEID), nicholas.tyack@graduateinstitute.ch.

Acknowledgements: I would like to thank colleagues at the Graduate Institute for their useful comments and inputs at the department BBL and Development Therapy seminars. In addition, particular thanks are due to Tim Swanson, Jean-Louis Arcand, Roxana Manea and Pedro Naso for their useful comments and suggestions.

1. Introduction

Innovation and technological change are seen as being key drivers of economic growth in modern endogenous growth theory, building upon early work such as Solow (1956, 1957) and more recently in Romer (1990) and Aghion and Howitt (1992). An essential component of successful innovation processes is the concept of diffusion; indeed, a new invention or technology has minimal impact in cases where it is adopted by very few. Furthermore, diffusion tends to occur with uneven success in different communities and regions (Griliches 1957). Thus, empirical insights into what drives successful diffusion of technology are of great interest for the field of innovation economics and for understanding the factors contributing to economic growth more broadly. An active literature has explored various issues connected to diffusion in recent years related to organizational barriers (Atkin et al. 2017), productivity impacts of intentional technology transfers (Giorcelli 2019), spatial aspects (Agrawal et al. 2017; Roche 2020), the role of patents in diffusion (Cockburn et al. 2016), the impact of information technology (Arrow, Bilir and Sorenson 2020), and agriculture (Conley and Udry 2010; Gross 2018; Kantor and Whalley 2019; Gupta et al. 2020).

In this paper, I contribute to this recent literature by using the Green Revolution as a natural experiment of diffusion to investigate first the extent to which the spread of modern varieties led to country-level yield growth, and second whether the diffusion of modern varieties led crop yields in developing countries to converge to those in developed countries. I further investigate whether diffusion took place strictly in an imitative fashion (following Barro and Sala-i-Martin 1997) or whether successful diffusion can be better understood as an adaptive process in which foreign innovations (in this case high-yielding crop varieties such as IR-8) must be adapted to local conditions, requiring institutional and regulatory capacity in the developing country receiving the technology, as well as domestic research and development (R & D) investments, as argued by Ruttan and Hayami (1973) and Evenson (2004). To this end, I build upon Bloom et al. (2020) to develop an "innovation production function" for crop variety development in the context of the Green Revolution in order to empirically test different factors contributing to successful diffusion.

In the context of development economics, the diffusion of agricultural technology is of particular interest given the large productivity gap between developed and developing country agriculture as well as the large proportion of individuals involved in the agriculture sector in developing countries.[1] A major focus in development

[1]The majority of the world's poor depend on agriculture for their livelihoods, with

has thus been on the idea that an emphasis on increasing agricultural productivity – "agriculture first" – can hasten the start of industrialization and lead to beneficial structural transformation by freeing up labor from the agriculture sector and enabling workers to move to more productive jobs in manufacturing or services (Gollin, Parente and Rogerson 2002). Diffusion is a key factor in such strategies to increase agricultural productivity in the developing world – namely the idea that productivity-enhancing technologies can be diffused from the productive agriculture sectors of developed countries to the low-productivity farmers of developing nations, helping them to converge towards the technological frontier (Ruttan and Hayami 1973). Effective international diffusion of agricultural technology is thus seen as a particularly promising approach to development and poverty reduction (Ligon and Sadoulet 2018), making a greater understanding of this process of interest in the field of development economics.

To investigate this research question – of whether this substantial investment in technology diffusion led to yield growth and convergence in the developing world, and whether adaptive innovation and capacity in developing countries was important for successful diffusion – I combine data from Evenson and Gollin (2003b) on the adoption of modern varieties across a panel of a number of developing countries between 1960 and 2005 with data on a number of inputs (such as tractors, fertilizer, and labor). In addition, following Hayami and Ruttan's model of diffusion and international technology transfer, I also include variables related to the domestic capacity of developing countries to successfully receive modern varieties through adaptive research and development, such as country-level research and development expenditures in the agriculture sector as well as intellectual property right regimes (Ruttan and Hayami 1973), and additionally investigate the role played by hybrid technology in either enhancing or restricting the diffusion of genetic resources, by focusing the analysis on two hybrid (maize and sorghum) and two non-hybrid (rice and wheat) crops.

This analysis is of interest both for the insight it can provide looking backwards - at how investments in breeding more productive crops impacted the ability of developing countries to "catch up" to the technological frontier - and also for the future, as it provides an analysis of the extent to which investments in breeding better crop varieties might help to reduce yield gaps across the developing world. Currently, discussions are ongoing as to the extent that a new "Green Revolution" can con-

some of the poorest countries such as Burundi and Mozambique possessing agriculture employment shares of more than 75 percent (Wingender 2014).

tribute to many of the Sustainability Development Goals, such as those related to reducing poverty and improving food security. However, the history of the Green Revolution is contested and a better understanding of the past is necessary to better inform future decisions and investments in the 21st century. This research has the potential to shed light on how successful such investments may be in accomplishing these goals, and to provide quantitative, empirical evidence for the impacts of the past diffusion of improved crop varieties on yield growth and reductions in the yield gap in the agriculture sectors of developing countries.

In addition, this article's investigation of *how* successful diffusion occurs is of great relevance for how development efforts are structured: should funds be invested primarily to aid diffusion of already existing technologies from the developed world, or should efforts also be made to strengthen innovation, institutional and regulatory capacity in developing countries as well? Does innovation only occur at the technological frontier or should adaptive innovation in countries "receiving" foreign technologies also be emphasized as a key component of successful diffusion processes? While this analysis focuses on diffusion in agriculture, the questions it addresses may additionally be relevant for understanding technology diffusion more generally.

The rest of the article is organized as follows. I first provide a brief summary of the related literature to which this study contributes, and then present the theoretical background of the empirical work. Next, I describe the data used, methodology and empirical approach, while in the fourth section I present the main empirical results. The fifth section concludes and discusses some of the implications of the empirical findings.

2. Related Literature

This paper aims to investigate how the diffusion of improved genetic resources contributed to productivity growth as well as a reduction in yield gaps (i.e., convergence towards the yield frontier) for four crops across a number of developing countries in the second half of the 20th century. The analysis thus lies at the intersection of two related fields of the economics literature: one focusing on the determinants of agricultural productivity (and particularly crop productivity, i.e. yields) globally and its change over time, and a recent literature investigating the diffusion of modern high-yielding crop varieties in the developing world and associated impacts as a result of the Green Revolution.

The first field of related literature has attempted to explain international productivity patterns in agriculture based on a number of variables (such as research and development expenditures, convergence, etc.). Fuglie et al (2012) illustrate the unevenness of productivity growth across countries. One explanation for these differences may be related to research and development, the focus of Madsen and Islam's (2016) investigation of the impact of research and development investments on land productivity. Using data for 90 developed and developing countries, they find that R&D knowledge stock has a positive and significant impact on land productivity using an instrumental variable approach. Islam and Madsen (2018) explore the interactions between research and development and ecozones and their impacts on labor productivity. Other papers, such as Goeschl and Swanson (2000) and Goeschl and Swanson (2003), have explored whether crop yields in the developing world converge based on countries' distance to the technological frontier. And more recently, Spielman and Ma (2016) investigate in a similar framework the contribution of legal intellectual property regimes to convergence for six major crops, while McArthur and McCord (2017) analyze the impacts of fertilizer, modern seeds and irrigation on cereal yields with a cross-country dataset composed of 69 countries.[2]

The second area of literature this research builds upon is a group of papers that analyzes various impacts resulting from the unprecedented diffusion of improved crop varieties seen as a consequence of the Green Revolution. The Green Revolution was a major public sector investment in the development of improved crop varieties that led to the uptake in many developing countries of a package of fertilizers and high-yielding modern varieties and large corresponding increases in crop production and productivity (Pingali 2012). The core of this episode of agricultural innovation began with the foundation of the International Rice Research Institute in the Philippines

[2]Several of these papers address the potential impact of both "weak" institutional sources of intellectual property protection such as plant variety protection and "strong" technological sources of intellectual property protection such as hybrid technology, which help to address a recurring issue in the plant breeding industry, namely that in many cases the appropriation of the benefits of any new crop variety is as simple as re-planting the seed after the first harvest. Hybrid crop varieties require carefully maintained male and female "parental" lines (which are used to produce hybrid seed) to obtain the yield benefits associated with heterozygote vigor (that is, they cannot simply be replanted by farmers and still offer a yield advantage), and are thus beneficial for private seed companies since the production of hybrid seed requires more specialized operations than the seed of open-pollinated varieties. Hybrid varieties can be considered to be predecessors of so-called "genetic use restriction technologies" (GURTs), defined as "a range of molecular strategies designed to impede transgene movement" (Hills et al. 2007).

in 1960 and the organization of the International Maize and Wheat Improvement Center in Mexico City in 1966. While wheat and rice are the most well-known Green Revolution crops, a number of other such international research centers focusing on other crops later joined these two initial institutions, together constituting a major network of international agricultural research centers called the Consultative Group on International Agricultural Research (CGIAR). These research centers created large genetic resource collections (genebanks) for the specific crops they covered and worked to develop and disseminate advanced breeding lines and high yielding varieties to national agricultural research systems across the developing world (Evenson 2005). The Green Revolution offers a "natural experiment" to study agricultural technology diffusion and the corresponding impacts on crop-level productivity and yield gaps as it marks a major investment by the developed world to favor and enhance the free diffusion of improved crop varieties to the developing world. This case is of interest given that it was an *intentional* transfer of technology - thus some of the usual frictions to diffusion were not present. Indeed, countries at the technological frontier typically attempt to prevent or slow the diffusion of their technologies to other nations in order to maintain their edge (through intellectual property protection and other measures).

One of the first major investigations of the impacts of the Green Revolution is provided by Evenson and Gollin (2003), who utilize an international multimarket model (IMPACT) and find that the Green Revolution increased crop yields and production and decreased crop prices and child malnourishment in developing countries substantially. More recently, Barnwal et al. (2017) and Goltz et al. (2020) have analyzed the impact of modern crop variety diffusion on infant mortality based on data from 36 developing countries, and find using village, country and year fixed effects that the spread of high-yielding crop varieties led to around a 3 to 4 percent decrease in infant mortality and averted around 3-5 million infant deaths per year by 2000. Bharadwaj et al. (2018) have similarly investigated the impact of the Green Revolution and the corresponding increase in high-yielding variety acreage on infant mortality in India, while Gollin, Hansen and Wingender (2019) analyze the impact of the modern variety diffusion that occurred as a result of the Green Revolution on per capita GDP, finding a positive impact on crop yields and GDP growth and a negative impact on population growth and the area of land under cultivation.

In addition to the insights it provides for the broader diffusion literature, this research also contributes to these two more specific streams of related literature on agricultural productivity growth (Spielman and Ma 2016; Madsen and Islam 2016;

McArthur and McCord 2017) and a body of several recent papers on the impacts of the Green Revolution (Barnwal et al. 2017; Bharadwaj et al. 2018; Gollin et al. 2019; Goltz et al. 2020) by disentangling the contribution of the diffusion of modern crop varieties to yield growth and convergence in the developing world from other inputs, providing a focus on the role played by improved crop varieties in the process of technological change in agriculture, and additionally exploring the importance of developing country institutions and domestic investments in research and development to successful technology diffusion. Investigating the contributions of improved crop varieties to agricultural productivity convergence in the developing world has the potential to inform policymakers about the role investments in genetic resource improvement may have in the 21st century in terms of increasing food production while using less land and a smaller agricultural labor force by providing insight into the 20th century productivity impacts of plant breeding. Additionally, the article's focus on domestic contributors to adaptive diffusion has the potential to help provide a better understanding of diffusion processes from countries at the technological frontier to developing countries.

3. Theoretical Background

This paper's analysis is rooted in Hayami and Ruttan's theory of induced technical change, in which agricultural productivity growth is driven by induced technological innovation rather than a slow process of capital accumulation (Hayami and Ruttan 1970; Binswanger and Ruttan 1978).

Within this theoretical framework, innovation – the development and application of new technology – is seen as endogenous to the economic system. The substantial increases in agricultural productivity over the past 150 years are thus characterized as having been driven by a series of technological revolutions.[3] This earlier theory of induced technological innovation can be placed within the later, more general endogenous growth theory framework, in which economic growth is driven by endogenous improvements in the level of technology (Romer 1990).

In this section, I develop an innovation production function for new crop varieties, following from the work of Bloom et al. (2020), to investigate which factors contributed to the successful diffusion of modern varieties during the Green Revolution.

[3]Examples of these technological revolutions in agriculture include the mechanization revolution in the 1800s, the chemical revolution driven by the discovery of the Haber-Bosch process for industrially producing ammonia fertilizer in the early 20th century, and the advances in modern plant breeding driven by Mendelian hereditary genetics.

This innovation production function will be used to test my hypotheses related to the role played by developing country institutions and investments in promoting successful diffusion.

A. *Identifying drivers of yield productivity growth for "follower" countries*

Theoretically, crop-level productivity can be described using a Cobb-Douglas production function, following the path of a number of seminar early papers such as Hayami and Ruttan (1970). In addition, a variable "A" is added that represents the level of technology, while L represents labor, N represents land, F represents fertilizer use, and K represents agricultural capital such as machinery and livestock:

$$Y = \mathrm{A}L^{\alpha}N^{\beta}F^{\gamma}K^{1-\alpha-\beta-\gamma} \tag{1}$$

Within the framework of Hayami and Ruttan and endogenous growth theory, the primary focus is the evolution of the technology variable "A," which in the context of the Green Revolution can be considered to be modern, high-yielding crop varieties (the novel agricultural technology).

We can express a simple "innovation production function" as follows, where S_t represents some measure of research input such as research expenditures or the number of researchers working on a given crop (building upon the idea production function described in Bloom et al. 2020):

$$\frac{\dot{A}_t}{A_t} = \alpha S_t \tag{2}$$

Thus, the breeding and release of higher-yielding modern varieties can be expressed as a function of the investments made in research and development or alternatively as the number of researchers allocated to the development of new varieties of any given crop.

However, it is clear that international or foreign investments in research and development can also affect productivity through a process of international exchange of information and technology diffusion. Much of the diffusion literature has focused on the role trade plays in the diffusion of technology, with channels such as foreign direct investment and imports playing major roles (Keller 2004).

Following from Coe and Helpman (1995), equation (2) can thus be adapted to reflect that productivity growth or the evolution of the level of technology can be driven both by investments in research and development domestically (S_{it}^{D}) and also by foreign investments in research and development (S_{it}^{F}):

$$\frac{\dot{A}_t}{A_t} = \alpha_1 S_{it}^{D} + \alpha_2 S_{it}^{F} \tag{3}$$

In the context of this paper, I consider the case of developing countries whose crop-level yields lag behind those enjoyed in "leader" or "frontier" countries. Unlike in the context of technology diffusion through trade, the Green Revolution provides a case in which frontier countries invested in the diffusion of agricultural technology to intra-frontier countries while suspending frictions to the spread of technology such as intellectual property protection. Modern crop varieties, a product of foreign innovation, were transmitted to developing countries, diffusing embedded innovations such as the genes for dwarfing, reduced photoperiod sensitivity and early maturity in the case of rice and wheat.

According to the model of Barro and Sala-i-Martin (1997), innovation occurs at the technological frontier and "followers" catch up through a process of imitation – suggesting an important role for the "$\alpha_2 S_{it}^{F}$" term in equation (3) for the evolution of productivity growth in countries within the technological frontier. Productivity growth in their model is seen as being almost entirely driven by diffusion from the outside world to "follower" countries in the developing world.

We can further differentiate the term representing domestic innovation in equation (3). Given the importance of public sector investments in crop breeding in developing countries, notably the national agricultural research systems (NARS), I further elaborate this expression by distinguishing between domestic investments in R&D for crop variety development in the public and private sectors as follows:

$$\frac{\dot{A}_t}{A_t} = \alpha_1 S_{it}^{D,private} + \alpha_2 S_{it}^{D,public} + \alpha_3 S_{it}^{F} \tag{4}$$

Finally, I include interactions between domestic and foreign investments in research and development in crop breeding research to reflect the importance of adaptive capacity – that is, domestic investments in R&D to adapt imported foreign innovations to the local context.

$$\frac{\dot{A}_t}{A_t} = \underbrace{\alpha_1 S_{it}^{D,priv} + \alpha_2 S_{it}^{D,publ}}_{\text{Domestic innovation}} + \underbrace{\alpha_3 S_{it}^{D,priv} S_{it}^{F} + \alpha_4 S_{it}^{D,publ} S_{it}^{F} \alpha_5 S_{it}^{D,priv} S_{it}^{D,publ} S_{it}^{F}}_{\text{Adaptive diffusion}} + \underbrace{\alpha_6 S_{it}^{F}}_{\text{Imitative diffusion}} \tag{5}$$

In Equation (5), the first two terms represent productivity advances based upon "domestic" innovation carried out in the local private and public sectors without interaction with the outside world – that is, investments in developing new crop varieties using local genetic resources. The sixth term, "$\alpha_6 S_{it}^{F}$," represents foreign innovations that are imported and adopted without any further changes – such as the break-through rice variety "IR8," which in many cases was adopted by farmers in the developing world initially without further breeding efforts on the local level. Finally, the middle three terms represent the "adaptive" diffusion model proposed by Hayami and Ruttan, in which foreign technology is adapted to local conditions through investments made by the "follower" countries. The third term represents "adaptive" R&D by the private sector of the receiving country, the fourth term investments in adaptation by the public sector, and the fifth term adaptive investments in the public and private sectors that build off of each other synergistically.

4. Empirical Approach

In this section, I first describe the data utilized, my hypotheses, and finally the empirical approach taken – which includes both an analysis of how the diffusion of modern crop varieties affected crop-level productivity growth as well as an analysis of how the adoption of modern crop varieties contributed to the convergence of developing country crop yields towards the yield frontier for the four crops I examine.

A. Data

Yield data and the area planted for each of the four crops (rice, wheat, maize, and sorghum) were downloaded from FAOSTAT for the developing countries for which data on high-yielding variety adoption was available and converted into five-year averages. "Leader" countries representing the frontier were selected for each five-year period from a universal set of countries growing each of the four crops and their five-year average yield for each period was taken as the frontier yield value. The yield gap for each developing country was calculated as the difference between their five-year average yield and the frontier yield.

Data on other inputs were added from Fuglie (2012), including a number of variables for 77 developing countries over the 1960 - 2005 time period (in five-year averages), including the number of cattle-equivalent heads of livestock on farm, the number of on-farm machinery units in use (in 40-CV tractor-equivalent), the tons of N-fertilizer equivalents used, labor (in thousands of economically active individuals in the agriculture sector) and land (in thousands of hectares). This data originates from FAOSTAT, with some supplementary data from national statistical sources.

I use the data from Fuglie (2012) because of efforts made to adjust some input measures for quality, for example by weighting land estimates by irrigation type. I render the input variables comparable between countries by dividing each by the number of hectares in agricultural production for the given country. National agricultural R & D expenditures calculated using teh perpetual inventory method (with a 15 percent depreciation rate) and measured in purchasing power parity are taken from Madsen and Islam (2016), and are weighted by the economy-wide gross domestic product. Intellectual property right index data is taken from Ginarte and Park (1997).

In addition, I add data from Evenson and Gollin (2003b) on approximate high-yielding variety (HYV) adoption rates for four major food corps: maize, rice, sorghum, and wheat. These estimates – based on careful review of data from national and international agricultural research centers – are used as a key proxy for the level of adoption of modern varieties for the four focal crops of the paper's analysis.

In addition to the use of adoption rates of modern varieties (representing the imported foreign innovation), I also use the following proxy variables to capture developing country contributions to diffusion: country-level research and development expenditures in the previous five-year period (representing domestic public sector investments in innovation), the intellectual property regime in the previous period (representing the country's regulatory capacity and potential to provide incentives to private-sector firms), and whether or not the crop in question is easily hybridizable (which I use as a proxy for private sector seed and breeding companies). I summarize these proxy variables in Table 1.

Table 1: Sources of innovation and proxy variables

Source of innovation	Institution	Proxy variable
Foreign		
R & D investments in the developed world	International agricultural research centers	Adoption rate of modern varieties
Domestic		
Domestic public sector	National Agricultural Research Organizations	National Agricultural R&D Expenditures
Domestic private sector	Private seed and breeding companies	Crop hybridizability
	Domestic regulatory capacity	Intellectual Property Rights regime

I use these proxy variables to capture the contributions of developing country institutions, regulatory capacity, and R&D investments to the success of diffusion efforts (measured as convergence towards the yield frontier).

B. Hypotheses

In this sub-section I describe three hypotheses I test in my empirical analysis related to the diffusion of modern crop varieties to developing countries during the Green Revolution.

My first hypothesis can be expressed as follows:

Hypothesis 1. The diffusion of modern crop varieties during the Green Revolution led to increases in crop-level yield growth (A) and/or convergence (B) of "follower" countries towards the yield frontier.

According to this hypothesis, diffusion (and the yield growth and convergence resulting from diffusion) can be explained purely by the dissemination of superior agricultural technology from the frontier to the lagging countries; that is, the evolution of "A" in developing countries can be explained strictly by the adoption rate of improved crop varieties. I test this hypothesis by running crop-specific regressions and determining whether changes in the adoption rate of modern varieties (or the interaction between changes in modern variety adoption and fertilizer use per hectare) for a given crop had a significant impact on productivity growth or yield convergence.

My second hypothesis is as follows:

Hypothesis 2. Those countries that were initially farthest from the technological frontier will experience greater productivity growth (A) and yield convergence (B) resulting from the adoption of modern varieties.[4]

I test this hypothesis by including an interaction term between each country's initial yield gap for each crop and the change in adoption rate of modern varieties.

If this hypothesis is correct, we would expect that the estimated coefficient for this interaction term would be positive and significant for yield growth and negative and significant for the evolution of the yield gap.

[4]This is a key feature of the model of Barro and Sala-i-Martin (1997), which postulates that imitation is easiest for countries that are the least productive initially, but that as these countries "catch up" to the frontier, the costs of imitation increase and the growth rate tends to decrease, leading to a pattern of conditional convergence.

However, if diffusion occurs in a more adaptive fashion, requiring local institutional and regulatory capacity, then the opposite of this assumption may hold true - instead of countries farthest from the technological frontier having the most capacity to absorb outside genetic information in the form of modern crop varieties, it may rather be that those developing countries in which yields were initially higher as a result of greater research and institutional capacity may have a greater capacity to adapt internationally developed modern crop varieties to their local environment (and may thus experience faster yield growth and convergence than those countries that were originally more distant from the frontier).

Last, I investigate a final hypothesis:

Hypothesis 3. Successful diffusion of modern crop varieties in the Green Revolution (i.e., leading to measurable yield convergence towards the technological frontier) was either (A) strengthened by or (B) required domestic investments in adapting the foreign innovations to local conditions.[5]

I test whether this hypothesis holds by including several interaction variables between the technology variable (the proportion of land devoted to a crop cultivated with improved varieties) and a number of variables capturing the country's indigenous innovation capacity and ability to successfully receive and adapt modern crop varieties through adaptive research and development. If Hypothesis 3 holds we would expect these interaction variables to be significant and negative for the evolution of the yield gap, indicating contributions to yield convergence.

C. Estimation Strategy

To address endogeneity concerns, I use more advanced dynamic panel data methods - namely the two-step system GMM estimator proposed by Arellano and Bover (1995) and Blundell and Bond (1998) - to investigate the extent to which productivity growth and yield convergence occurred for the four crops I analyze, conditional on modern variety adoption. This estimator, following the generalized method of moments (GMM) framework, uses internal instruments based on the lags of relevant variables to help to mitigate endogeneity concerns. I calculate robust standard errors using the Windmeijer (2005) finite sample correction, helping to provide more accurate inference.

I roughly follow the approach of Spielman and Ma (2016), and estimate the following regression for yield growth:

$$\Delta Y_{i,t} = c_i + \alpha_t + \beta \Delta Y_{i,t-1} + \varphi * \Delta A_{it} + \mu * \Delta A_{it} * G_{i,t=0} + \gamma_j \Delta X_{it} + \varepsilon_{it} \tag{6}$$

[5]This hypothesis can thus be split into two sub-components. First, Hypothesis 2A can be considered to be a weaker version, in which adaptive investments contribute to yield convergence. Second, Hypothesis 2B is a strong version that states that domestic investments in adapting foreign technology was a necessary condition for any yield convergence resulting from the adoption of modern varieties.

Here, ΔY_{it} represents the yield growth for a given crop in a given country in period t, $\Delta Y_{i,t-1}$ represents the yield gap in the previous period, ΔX_{it} represents a vector of the changes in the use of other inputs including fertilizer, labor, land, and machinery such as tractors, ΔA_{it} represents the change in technology (the change in the adoption rate of modern varieties for a certain crop or the change in the package of fertilizer use interacted with increase in the modern variety adoption rate), and finally $\Delta A_{it} * G_{i,t=0}$ represents an interaction of the change in the level of technology with the country's initial yield gap in the first period.

Second, I decompose the evolution of the yield gap as follows:

$$G_{it} = c_i + \alpha_t + \beta G_{i,t-1} + \varphi * \Delta A_{it} + \mu * \Delta A_{it} * G_{i,t=0} + \gamma_j \Delta X_{it} + \varepsilon_{it} \tag{7}$$

Here, G_{it} represents the yield gap for a given crop in a given country in period t, $G_{i,t-1}$ represents the yield gap in the previous period, ΔX_{it} represents a vector of other inputs including fertilizer, labor, land, and machinery such as tractors, ΔA_{it} represents the change in technology (the change in the adoption rate of modern varieties for a certain crop or the change in the package of fertilizer use interacted with increase in the modern variety adoption rate - or the change in the adoption rate of modern varieties interacted with the other variables of interest), and finally $\Delta A_{it} * G_{i,t=0}$ represents an interaction of the change in the level of technology with the country's initial yield gap in the first period.

5. Results

In this section, I first present the results of the productivity growth and convergence (yield gap) analyses carried out using crop-level regressions, and then the results of a pooled estimation including proxy variables. The crop-level analyses are conducted to test my first and second hypotheses, while the pooled estimations are designed to further investigate my third hypothesis, related to the role of domestic adaptive capacity in the successful diffusion of genetic resources. Both analyses are estimated using a two-step Arellano-Bond GMM estimator.

A. Productivity Analysis - Crop-Specific Estimations

I now present the results for the crop-level regressions for yield growth, which are carried out to test Hypothesis 1A and 2A for each individual crop (that is, that yield growth occurred as a result of adoption of foreign innovations, in this case modern crop varieties). The dependent variable is the country-level and crop-specific change in yields, measured as the difference between the five-year average yield of the country in period t and that country's five-year average yield in the previous period. The other variables enter the estimation in first differences.

In Table 2, I find that positive changes in the adoption rate of modern varieties of wheat and sorghum led to significant productivity increases, supporting the predictions of Hypothesis 1A. The interpretation of the coefficients indicates that a 10 percent increase in the the proportion of land cultivated with modern varieties of wheat led to a yield increase of 2,375 hectograms (about 238 kilograms) per hectare, and for sorghum led to a yield increase of 8,713 hectograms (871 kilograms) per hectare. These results support the predictions of Hypothesis 1A for both wheat and sorghum.

I find that the adoption of modern rice varieties (by themselves) did not lead to significant increases in productivity. In addition, the significant result of the AR(2) test for maize indicates that the regression results for the crop are not robust.

In addition, the interaction term for both of these crops with the country's initial yield gap are both significant and negative, indicating that those countries that were originally farther from the yield frontier for wheat and sorghum benefited less in terms of productivity increases from the adoption of modern varieties. [6]

[6] The interpretation of the coefficients are as follows. For wheat, the positive productivity impact described above stemming from the adoption of modern varieties is decreased by -0.078 hectograms per hectare for every hectogram per hectare the country was farther from the yield frontier for wheat in the initial period (or alternatively, is decreased by 780 hectograms per hectare for every metric tonne per hectare in distance from the frontier of the country in the initial period). Similarly, for sorghum, the positive productivity impact described above stemming from the adoption of modern varieties is decreased by -0.287 hectograms per hectare for every hectogram per hectare the country was farther from the yield frontier for sorghum in the initial period (or alternatively, is decreased by 2,870 hectograms per hectare for every metric tonne per hectare in distance from the frontier of the country in the initial period).

Table 2: Arellano-Bond estimates for contributors to productivity increases for wheat, rice, sorghum and maize

	YIELD GROWTH			
Explanatory variable	(Wheat)	(Rice)	(Sorghum)	(Maize)
Yield growth, first lag	0.094***	0.101	-0.235	0.893***
	(0.223)	(0.157)	(0.142)	(0.139)
ΔProportion modern varieties	**2,374.917*****	6,656.497	**8,713.389*****	2,203.370
	(767.247)	(5,016.25)	(2,076.342)	(3,402.369)
ΔProportion modern varieties x Initial yield gap	**-0.078****	-0.140	**-0.287*****	-0.099
	(0.031)	(0.109)	(0.073)	(0.087)
Other inputs				
$\Delta(labor/land)$	-14,001.11***	-6,084.306	1,794.097	-887.930
	(3,542.304)	(4,699.582)	(2,065.586)	(5,770.414)
$\Delta(fert./land)$	34.061	7.064	-0.485	35.435*
	(34.397)	(54.349)	(24.238)	(19.027)
$\Delta(machinery/land)$	-232.955	36.043	157.944	280.802*
	(198.968)	(172.563)	(83.216)	(125.670)
$\Delta(livestock/land)$	548.605	-625.465	-536.962	-2,921.967
	(1091.626)	(2,475.691)	(729.512)	(2,444.029)
$\Delta(areaplanted)$	0.000	0.000	-0.001	-0.000
	(0.000)	(0.001)	(0.000)	(0.001)
AR(1) p-stat:	0.050	0.012	0.090	0.164
AR(2) p-stat:	0.403	0.725	0.369	0.079
Hansen p-statistic	0.371	0.148	0.716	0.489
Number of countries	48	67	58	73
Number of observations	276	392	323	414
Number of instruments	47	63	52	68

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust (Windmeijer) standard errors in parentheses. The proportion of modern varieties variable enters the regression in multiples of ten percent.

The finding for these interaction terms for wheat and sorghum do not support the prediction of Hypothesis 2A, that those countries originally farthest from the yield frontier would experience greater productivity benefits from the adoption of modern varieties; in fact, they suggest that those countries farthest from the frontier experienced *reductions* in yield growth as a result of modern variety adoption.[7]

Next, I add an interaction term between changes in the use of fertilizer per hectare and changes in the adoption level of modern varieties for each crop. The results of this regression are shown in Table A1 in the appendix. I find that the interaction term between increased adoption rates of modern varieties of rice and increases in the use of fertilizer is positive and significant. The interpretation of the coefficient is that a concurrent increase of 10 percent in rice modern variety adoption coupled with an increase in average fertilizer use of one metric tonne of N-fertilizer equivalents per hectare led to a productivity increase of 72 hectograms per hectare.

The results for sorghum in this regression are similar to the results shown in Table 2, with the positive changes in the adoption rate of modern sorghum varieties leading to greater yield convergence, while neither the change in fertilizer use variable nor the fertilizer-modern variety interaction are shown to be significant (in addition, the interaction with the initial yield gap is no longer shown to be significant). The results for wheat are similar to those in Table 2. Last, it can be observed from the Hansen p-statistic for the maize regression that the identification is too weak to provide insights into the effect of the main variables of interest on yield growth.

To summarize, as a result of these regressions we find support for Hypothesis 1A, indicating that the adoption of modern varieties led to yield growth for wheat and sorghum, and the adoption of the package of fertilizer and modern varieties led to yield growth for rice. However, Hypothesis 2A is not supported; in fact, the results provide evidence that the opposite of its prediction is true in the case of wheat and sorghum (that is, those developing countries initially closest to the yield frontier experienced the greatest productivity benefits from modern variety diffusion).

[7]The interpretation for both crops is that countries whose initial yield gap was around three tonnes per hectare experienced no productivity benefits from the adoption of modern varieties; that countries whose initial yield gap was less than three tonnes per hectare experienced increasing productivity benefits from modern variety adoption (depending on how close they were to the yield frontier); and that countries whose initial yield gaps were greater than three tonnes per hectare in fact experienced productivity *declines* from the adoption of modern varieties.

B. Convergence Analysis - Crop-Specific Estimations

I now present the results of crop-level regressions that analyze the impact of modern variety adoption on the country's yield gap (distance to the technological frontier), in order to test Hypotheses 1B (regarding whether the adoption of modern varieties led to yield convergence) and 2B (regarding whether countries with larger initial yield gaps converged more quickly as a result of modern variety adoption).

I first investigate whether increased use of modern varieties for each crop contributed to a reduction in the given country's aggregate yield gap – as well as an interaction term with the country's yield gap in the initial period, to identify if high-yielding variety technology contributed to convergence among developing countries. These results are shown in Table A2 in the appendix. I then run a similar regression that includes an interaction term between the change in modern variety adoption and the change in the use of fertilizer, to test whether this interpretation of Green Revolution technology led to yield convergence for the four crops considered (Table 3).

In Table A2, it can be seen that the variables capturing the change in the proportion of cropland cultivated with modern varieties are only significant for sorghum. A national increase in the adoption of modern, high-yielding sorghum varieties led to a substantial decrease in the sorghum yield gap for that period (equivalent to 12 percent of the frontier yield value), supporting the prediction of Hypothesis 1B.[8]

The interaction term between modern variety adoption and the sorghum yield gap in the initial period is also significant, but instead positive, indicating that countries that were initially closer to the yield frontier for sorghum converged more rapidly towards the technological leader as a result of adoption of modern sorghum varieties than did those that were originally farther from the sorghum yield frontier (this finding is exactly the opposite of that predicted by Hypothesis 2B).[9]

[8]The dependent variable in both regressions is the country-level and crop-specific yield gap, measured as the ratio between the five-year average yield of the country and the five-year average yield of the leader country for that period. The other variables enter the estimation in first differences.

[9]The interpretation of the coefficient is that only those countries whose yield gaps were originally around 50 percent of the yield frontier or less experienced convergence as a result of modern variety adoption. Conversely, those countries whose initial yield gaps were greater than 50 percent of the yield frontier experienced yield divergence as a result of modern variety adoption. This supports exactly the opposite of the prediction of hypothesis 2B.

Table 3: Arellano-Bond estimates for the evolution of the yield gap for wheat, rice, sorghum and maize - with fertilizer interaction

	YIELD GAP			
Explanatory variable	(Wheat)	(Rice)	(Sorghum)	(Maize)
Yield gap, first lag	1.007***	0.932***	0.867***	1.312***
	(0.047)	(0.149)	(0.079)	(0.110)
ΔProportion modern varieties	0.016	-0.063	**-0.113***	0.204
	(0.020)	(0.100)	(0.067)	(0.137)
ΔProportion modern varieties x Initial yield gap	-0.020	0.078	**0.242***	-0.232
	(0.025)	(0.131)	(0.145)	(0.161)
ΔProportion modern varieties x $\Delta(fert./land)$	-0.000	**-0.001****	-0.001	**-0.001****
	(0.000)	(0.000)	(0.001)	(0.001)
Other inputs				
$\Delta(labor/land)$	0.179	0.065	0.002	-0.013
	(0.049)	(0.062)	(0.038)	(0.017)
$\Delta(fert./land)$	-0.000	0.000	0.000	0.002
	(0.000)	(0.000)	(0.000)	(0.001)
$\Delta(machinery/land)$	0.003	-0.000	0.002	-0.003
	(0.003)	(0.001)	(0.002)	(0.004)
$\Delta(livestock/land)$	-0.002	0.015	0.004	0.002
	(0.011)	(0.028)	(0.013)	(0.007)
$\Delta(areaplanted)$	-0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
AR(1) p-stat:	0.002	0.001	0.001	0.034
AR(2) p-stat:	0.249	0.440	0.716	0.299
Hansen p-statistic	0.124	0.483	0.978	0.144
Number of countries	48	67	58	73
Number of observations	276	302	323	438
Number of instruments	44	64	54	64

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust (Windmeijer) standard errors in parentheses. The proportion of modern varieties variable enters the regression in multiples of ten percent.

In Table 3, where I add an interaction term between changes in the use of fertilizer per hectare and changes in the adoption level of modern varieties for each crop, I find that this interaction is significant and negative for rice and maize, indicating that concurrent increases in the adoption rate of high-yielding rice and maize varieties and the use of fertilizer led to a reduction in the country's yield gaps for that period. The results for the wheat regression indicate that the diffusion of modern varieties of wheat did not lead to yield convergence, in spite of the productivity increases associated with adoption.[10]

To summarize the results for this section, I find that the adoption of modern varieties (by themselves) contributed to yield convergence for sorghum, but not for the other three crops. Yield convergence was found to be driven by the joint adoption of fertilizer and modern varieties for maize and rice. These results support the predictions of Hypothesis 1B for sorghum, rice and maize, but not for wheat. Additionally, I find evidence that countries whose sorghum yields were initially closest to the yield frontier were able to converge more quickly, the opposite of the prediction of Hypothesis 2B, and in fact those countries whose initial yield gaps for sorghum were the largest experienced yield *divergence* as a result of modern variety adoption.

C. Convergence Analysis - Pooled Estimations

In this section, I present the results of the pooled convergence analysis, which I use to test Hypothesis 3, that domestic country institutions and adaptive capacity either contributed to (3A) or were necessary (3B) for successful diffusion leading to yield convergence.

I start by including a number of interaction variables associated with the first lag of the level of intellectual property protection in the country as well as whether or not the crop in question is commonly commercialized through hybrid variety development (as is the case for maize and sorghum).[11] This regression is run to

[10] An interpretation of this finding is that while the adoption of modern wheat varieties helped contribute to productivity increases in developing countries, these productivity increases were not enough to lead to significant yield convergence (that is, the yield frontier was moving faster than the productivity enhancements provided by modern variety adoption).

[11] It should be noted that hybrid rice varieties do exist; however, these are much less common and widely adopted as for maize and sorghum.

better understand any potential role played by intellectual property regulations and developing country private seed sector companies in promoting yield convergence resulting from the successful diffusion of genetic resources. The results from this regression are presented in Table A3 in the appendix.

The results show that an increase in the adoption rate of modern varieties of both commonly hybridizable and not commonly hybridizable crops led to a reduction in the yield gap.[12] However, the interaction with the initial yield gap indicates that the countries with larger initial yield gaps experienced lower convergence gains.[13] In addition, the interaction between the change in the proportion of modern varieties cultivated for a crop, whether that crop is hybrid and the first lag of the level of intellectual property right protection is significant and negative, indicating that the level of intellectual property protection in the previous period coupled with higher adoption of modern varieties of the crop led to a higher reduction in the associated yield gap for the developing country in question (for hybrid crops). The coefficient is about 2.5 times larger than that for changes in the adoption rate of modern varieties by itself, indicating that if a country had an IPR index of 1 in the previous period, the benefit in terms of yield convergence for adopting modern varieties of a hybrid crop would be approximately three and a half times higher than for a country with an IPR index of 0.

However, the interaction between whether or not a crop is hybrid, the change in the modern variety adoption rate for that crop, the country-level regime of IPR protection in the previous period, and the yield gap in the initial observation for each country is significant and positive, indicating that the benefits of IPR protection for hybrid crops in terms of leading to reductions in the size of the yield gap is greater for countries that were closer to the frontier at the beginning of the timeframe covered by the dataset.[14] In addition, if the crop was not easily commercializable as a hybrid,

[12]The interpretation of the coefficient is that an increase in 10 percent of the area cultivated with modern varieties led to 7.4 percent reduction in the yield gap. This is consistent with the "imitative" model of diffusion - that is, that adoption of the technology as is led to convergence.

[13]For example, for an initial yield gap of 0.5 (indicating a gap equivalent to half the frontier yield value), the convergence benefit of a 7.4 percent reduction in the yield gap resulting from an increase in the adoption rate of modern varieties of 10 percent would be reduced by 3.15 percent, leading instead to just a 4.25 percent reduction in the yield gap.

[14]As an example, for an initial yield gap of 0.5 (indicating the original yield gap was equivalent to half the frontier yield value), the benefit of intellectual property protection

as for rice and wheat, I find that a more stringent intellectual property protection regime in the previous period led to an increase in the yield gap in spite of increases in the adoption of modern varieties.[15]

An interpretation of these results is that greater levels of intellectual property right protection potentially fostered greater involvement of private firms in the case of maize and sorghum, leading to a reduction in the size of the yield gap for these crops when coupled with increased adoption of modern varieties – but not for rice and wheat, for which investments in breeding and research and development of new varieties were not protected by the characteristics of hybrid varieties (that is, that they do not maintain their yield superiority if re-planted by farmers). That is, perhaps firms were incentivized to invest in the creation of new varieties when they observed that they would benefit from a combination of institutional (in the form of IPR protection) and technological (in the form of hybrid technology) protection for the rents from their investment.

On the other hand, more stringent intellectual property protection regimes could have potentially led to less diffusion of improved rice and wheat varieties, but were not enough to incentivize private firms to innovate in the development and sale of improved rice and wheat varieties. These findings support Hypothesis 3A, and suggest that adaptive investments in the domestic private seed sector supported by IPR protection contributed to yield convergence - but only for hybrid varieties.

In Table 4, I include terms interacted with the first lag of the country-level agricultural R&D expenditure, deflated by the economy-wide GDP deflator and measured in purchasing power parity terms, encompassing both researcher salaries as well as other R&D resources including instruments, machinery, buildings, greenhouses, labs, land, etc. The goal of this regression and the addition of this variable is to capture any potential impacts of country-level R&D spending in the agriculture sector taking place.

for hybrid crops would be reduced from an 18 percent reduction in the yield gap to a 9 percent reduction in the yield gap.

[15]Additionally, a significant positive estimate for the interaction between the initial yield gap for a crop and whether or not the crop was a hybrid suggests that varieties of commonly hybridizable crops diffused less easily in countries with larger initial yield gaps.

Table 4: Estimates for the evolution of the yield gap - pooled dataset with R&D

Explanatory variable	Yield Gap
Yield gap, first lag	**0.993***** (0.082)
ΔProportion modern varieties	-0.072 (0.067)
ΔProportion modern varieties x Initial yield gap	0.055 (0.068)
ΔProportion modern varieties x $\Delta(fert./land)$	0.000 (0.000)
ΔProportion modern varieties x Hybrid	**-0.235** (0.126)
ΔProportion modern varieties x IPR$_{t-1}$	**0.021*** (0.012)
ΔProportion modern varieties x ln(R & D)$_{t-1}$	-0.001 (0.005)
ΔProportion modern varieties x Hybrid x IPR$_{t-1}$	0.113 (0.074)
ΔProportion modern varieties x Hybrid x ln(R & D)$_{t-1}$ x IPR$_{t-1}$	**-0.089**** (0.043)
ΔProportion modern varieties x Hybrid x ln(R & D)$_{t-1}$	**0.171**** (0.076)
Hybrid x ln(R & D)$_{t-1}$	-0.016 (0.016)
Hybrid x IPR$_{t-1}$	0.001 (0.018)
IPR$_{t-1}$	0.004 (0.021)
ln(R & D)$_{t-1}$	-0.006 (0.010)
Other inputs	
$\Delta(labor/land)$	-0.016 (0.036)
$\Delta(fert./land)$	-0.001 (0.001)
$\Delta(machinery/land)$	-0.002 (0.004)
$\Delta(livestock/land)$	0.002 (0.015)
$\Delta(areaplanted)$	0.000 (0.000)
AR(1) p-stat:	0.000
AR(2) p-stat:	0.285
Hansen p-statistic	0.777
Number of groups	184
Number of observations	1,073
Number of instruments	173

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust (Windmeijer) standard errors in parentheses. The yield gap is in natural logs and calculated as a proportion of the frontier yield value.

I present several findings as a result of this estimation. I find that the adoption of modern varieties of commonly hybridized crops is found to lead to increased yield convergence (regardless of the level of IPR protection or research expenditure in the previous period).[16] In addition, I find that investments in agricultural research and development in the previous period contributed further to this yield convergence for hybrid crops with the presence of stronger IPR protection in the previous period when coupled with higher adoption of modern varieties. This finding suggests that synergistic investments in the private and public sector of developing countries helped to contribute to greater yield convergence as a result of the diffusion of modern Green Revolution varieties.

As before, I also find that higher IPR protection in the previous period is found to increase the yield gap for non-hybrid crops in spite of higher adoption of modern varieties. Last, in this regression I do not find that an increase in the adoption of modern varieties of non-hybrid crops by themselves led to yield convergence - instead this only occurred in the presence of other proxy variables selected to represent the “adaptive” diffusion model.

To summarize the results of the pooled regressions I present, I find evidence to support my third hypothesis, that developing country investments and institutions contributed to yield convergence. However, the different proxy variables I use are found to benefit different types of crops differently. Intellectual property rights are shown to contribute to yield convergence for hybrid crops, but slow convergence for non-hybrid crops. National agricultural R&D investments are shown to primarily contribute to greater yield convergence of hybrid crops in countries with higher IPR protection. And last, I find no evidence that domestic innovation contributed to yield convergence in the absence of changes in modern variety adoption.

6. Conclusion

In this paper, I use the Green Revolution as a natural experiment of technology diffusion to analyze how increases in adoption rates of modern varieties of four crops during the Green Revolution period led or did not lead to yield growth and convergence in a number of developing countries. I further investigate the extent to which developing country institutions, R&D investments, and regulatory capacity

[16] The estimated coefficient of -0.235 indicates that a ten percent increase in the adoption rate of commonly hybridized crops led to a 23.5 percent reduction in the size of the yield gap.

contributed to the success of diffusion.

I find some evidence that modern crop varieties on their own contributed to yield growth and convergence for several crops. In simple, crop-level regressions, I find that increases in the adoption rates of modern varieties of wheat, sorghum, and the "package" of fertilizer use and the cultivation of modern rice varieties led to productivity increases for these crops. In addition, I find that adoption of modern variety technology led to significant reductions in yield gaps for sorghum, and that adoption of the package of fertilizer and modern varieties led to significant (but smaller) reductions in yield gaps for rice and maize.

I additionally utilize a pooled regression for all four crops to test the extent to which developing country adaptive capacity contributed to successful diffusion, in which I include variables including the lagged IPR index and R&D expenditures as well as the hybridizability of the crop as a proxy for the efforts of the developing country's private and public sectors in adapting modern variety technology to the local environment. I use these proxy variables to explore the role played by hybrid technology in either enhancing or restricting the diffusion of genetic resources, as well as that played by IPR protection and country-level research and development expenditures in the agriculture sector.

I find some evidence for the validity of the prediction that domestic country institutions play a significant role in successful diffusion processes. However, the contributions of these institutions to yield convergence are found to have had different impacts on different crops, depending on whether or not they were commonly found as hybrid varieties during this period. I find that increases in adoption rates of modern varieties for which hybrid varieties are common led to larger reductions in the crop-specific yield gap when intellectual property right protection levels were higher in the previous period. This effect is found to be greater for countries that were initially closer to the yield frontier. And in the case of rice and wheat, which are not as easily commercializable as hybrid varieties, I find that the presence of a stricter intellectual property protection regime in the previous period led to an increase in the yield gap, in spite of increases in the adoption of modern varieties.

I also investigate the assumption of Barro and Sala-i-Martin (1997) that those countries farthest from the frontier are those most able to absorb foreign innovations and more rapidly converge towards the technological frontier. However, I find exactly the opposite in a number of cases. For example, I find that greater adoption of modern Green Revolution sorghum and wheat varieties contributed to yield growth, but to a *lesser* extent for countries that were originally farther from the sorghum yield frontier, providing some evidence of a "low productivity trap" for these crops. This pattern holds true in the case of the contribution of modern variety adoption to yield convergence for sorghum. Last, I find evidence that the benefits of higher intellectual property right regimes for hybrid crop yield convergence are lower for countries originally farther from the yield frontier, further supporting the opposite assumption, that it is in fact those developing countries that were originally closer to the yield frontier that benefited the most from the diffusion of modern crop varieties as a result of the Green Revolution.

More broadly, the dataset I utilize reveals some broader patterns related to innovation and crop-level productivity growth. Strikingly, the technological frontier for maize was 2.6 times higher by the end of the dataset than in the initial period, followed by wheat (about twice as high), sorghum (1.8 times the initial yield) and rice (1.5 times higher). Thus, the technological frontier moved higher more rapidly for crops that are more important for developed countries (maize and wheat), and crops that are more easily commercialized as hybrid varieties (maize and sorghum). This finding is intuitive – and suggests that breeding efforts focused on the crops that were most important for the countries with the most resources to invest, and also to a greater extent for crops for which some form of technological protection was available to protect the initial investment in breeding a new variety (i.e., hybridizability). In this context, we can see the Green Revolution as having led to much greater investments in breeding more productive varieties of rice and sorghum (predominantly developing country crops) than would otherwise have occurred, helping developing countries to catch up to developed country yields for these crops.

These results highlight the complexity associated with the international diffusion of agricultural technology, and demonstrate the importance of so-called "strong" forms of technological protection of intellectual property rights related to plant genetic resources, such as the development of hybrid crop varieties. In particular, the results show that "soft" institutional forms of IPR protection - coupled with the ability to commercialize hybrid varieties and increased adoption of modern Green Revolution varieties - contributed to yield convergence for such crops, potentially fostering greater involvement of private firms in the case of maize and sorghum. Higher agricultural research and development expenditures in this case were also shown to foster greater yield convergence, illustrating an interplay between the innovations taking place at international research organizations (i.e., the CGIAR system), public investments at the country-level by the national agricultural research organizations, and activities taking place in the private sector as well (as supported by the significant interaction terms with the level of strictness of the country's IPR regime).

These findings lend support to Hayami and Ruttan's conception of diffusion being an adaptive process, highlighting the importance of developing country innovation and institutional capacity for successful diffusion of technology from frontier countries. However, stricter intellectual property right protections were also shown to potentially restrict the diffusion of improved genetic resources in the case of non-hybrid crops (here, rice and wheat), leading to an increase in the yield gap for these crops, illustrating the important tradeoff between incentivizing further innovation and promoting the diffusion of productivity-enhancing technologies in the agricultural sector.

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Supplementary Appendix

Table A1: Arellano-Bond estimates for contributors to productivity increases for wheat, rice, sorghum and maize - with fertilizer interaction

	YIELD GROWTH			
Explanatory variable	(Wheat)	(Rice)	(Sorghum)	(Maize)
Yield growth, first lag	-0.027	0.093	-0.214	1.087***
	(0.204)	(0.149)	(0.129)	(0.169)
ΔProportion modern varieties	**2,619.089****	3,042.852	**6,879.518*****	-1,380.531
	(1,267.402)	(4,199.703)	(1,989.203)	(3,371.801)
ΔProportion modern varieties x Initial yield gap	**-0.075**** -0.063	-0.063	0.024	
	(0.037)	(0.092)	(0.092)	(0.081)
ΔProportion modern varieties x $\Delta(fert./land)$	-1.026	**72.223****	12.715	6.863
	(41.688)	(28.104)	(55.470)	(8.771)
Other inputs				
$\Delta(labor/land)$	-9,017.915***	-4,939.773	-428.109	-1,398.127
	(3,415.854)	(3,365.163)	(2,162.376)	(1,688.574)
$\Delta(fert./land)$	23.335	-24.001	15.035	7.198
	(38.059)	(37.034)	(14.690)	(9.288)
$\Delta(machinery/land)$	-1.129	81.858	-85.016	207.507
	(235.761)	(126.123)	(82.624)	(150.849)
$\Delta(livestock/land)$	295.127	-465.171	-121.046	-1,413.648
	(997.262)	(2240.679)	(574.067)	(2,655.426)
$\Delta(areaplanted)$	0.000	0.000	-0.001	-0.001
	(0.000)	(0.000)	(0.001)	(0.000)
AR(1) p-stat:	0.059	0.006	0.074	0.256
AR(2) p-stat:	0.594	0.724	0.448	0.176
Hansen p-statistic	0.684	0.881	0.986	0.039
Number of countries	48	67	58	73
Number of observations	276	392	323	438
Number of instruments	48	64	49	65

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust (Windmeijer) standard errors in parentheses. The proportion of modern varieties variable enters the regression in multiples of ten percent.

Table A2: Arellano-Bond estimates for the evolution of the yield gap for wheat, rice, sorghum and maize

	YIELD GAP			
Explanatory variable	(Wheat)	(Rice)	(Sorghum)	(Maize)
Yield gap, first lag	0.989***	0.926***	0.892***	1.282***
	(0.043)	(0.060)	(0.047)	(0.110)
ΔProportion modern varieties	0.008	-0.099	**-0.121****	0.132
	(0.020)	(0.082)	(0.049)	(0.103)
ΔProportion modern varieties x Initial yield gap	-0.010	0.121	**0.233****	-0.151
	(0.026)	(0.106)	(0.105)	(0.122)
Other inputs				
$\Delta(labor/land)$	0.170	0.027	0.019	0.010
	(0.040)	(0.043)	(0.040)	(0.032)
$\Delta(fert./land)$	-0.001	-0.000	-0.000	0.001**
	(0.000)	(0.000)	(0.000)	(0.001)
$\Delta(machinery/land)$	0.002	-0.000	0.003	-0.004
	(0.002)	(0.002)	(0.002)	(0.003)
$\Delta(livestock/land)$	-0.005	0.025	-0.00	0.003
	(0.011)	(0.028)	(0.015)	(0.007)
$\Delta(areaplanted)$	-0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
AR(1) p-stat:	0.002	0.001	0.001	0.041
AR(2) p-stat:	0.240	0.419	0.641	0.291
Hansen p-statistic	0.191	0.358	0.525	0.130
Number of countries	48	67	58	73
Number of observations	276	392	323	438
Number of instruments	47	63	57	73

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust (Windmeijer) standard errors in parentheses. The proportion of modern varieties variable enters the regression in multiples of ten percent. The yield gap is measured as the ratio between the five-year average yield of the country and the five-year average yield of the leader country for that period.

Table A3: Arellano-Bond estimates for the evolution of the yield gap - pooled dataset

Explanatory variable	Yield Gap
Yield gap, first lag	0.911***
	(0.057)
ΔProportion modern varieties	**-0.074****
	(0.037)
ΔProportion modern varieties x Initial yield gap	**0.063***
	(0.034)
ΔProportion modern varieties x $\Delta(fert./land)$	0.000
	(0.000)
ΔProportion modern varieties x Hybrid	0.038
	(0.038)
ΔProportion modern varieties x IPR$_{t-1}$	**0.017***
	(0.009)
ΔProportion modern varieties x Hybrid x IPR$_{t-1}$	**-0.180*****
	(0.065)
ΔProp. MV x Hybrid x IPR$_{t-1}$x Initial yield gap	**0.181****
	(0.080)
Hybrid x Initial yield gap	**0.057****
	(0.032)
IPR$_{t-1}$	0.023
	(0.014)
Other inputs	
$\Delta(labor/land)$	-0.024
	(0.037)
$\Delta(fert./land)$	-0.000
	(0.000)
$\Delta(machinery/land)$	-0.011
	(0.009)
$\Delta(livestock/land)$	0.009
	(0.011)
$\Delta(areaplanted)$	0.000
	(0.000)
AR(1) p-stat:	0.000
AR(2) p-stat:	0.256
Hansen p-statistic	0.406
Number of groups	184
Number of observations	1,072
Number of instruments	169

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Robust (Windmeijer) standard errors in parentheses. The yield gap is in natural logs and calculated as a proportion of the frontier yield value.