Genetic resources and agricultural productivity in the developing world

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Selected Paper prepared for presentation at the 2020 Agricultural & Applied Economics Association
Annual Meeting, Kansas City, MO
July 26-28, 2020

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Abstract

The Green Revolution was a major public sector investment in the development of improved crop varieties, especially for rice and wheat, that led to the uptake in many countries of a package of fertilizers and high-yielding modern varieties. This analysis aims to examine how these investments in the development and dissemination of improved crop varieties contributed (or did not contribute) to yield convergence and reductions in yield gaps for a number of crops across the developing world. This approach fits into the Hayami-Ruttan theory of induced technical change in agriculture, in which innovations in agricultural technology are seen as a primary driver of productivity growth in the sector (Hayami and Ruttan 1970). I investigate this question using a cross-country database on agricultural productivity, yields and modern variety adoption rates including 77 developing countries between 1960 and 2005. I employ panel data methods, including both fixed effects and Arellano-Bond estimators, 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. 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.

1. Introduction

The majority of the world's poor depend on agriculture for their livelihoods, with some of the poorest countries such as Burundi and Mozambique possessing agriculture employment shares of more than 75% (Wingender 2014). A major focus in development has thus been on the idea that an emphasis on increasing agricultural productivity – "agriculture first" – can hasten the start of industrialization and lead to structural transformation by freeing up labor from the agriculture sector (Gollin, Parente and Rogerson 2002). A key factor in such strategies to increase agricultural productivity in the developing world is the concept of *diffusion* – 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, thus 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 the economic growth in the agriculture sector that this strategy promises has been shown to be a particularly effective way to reduce poverty (Ligon and Sadoulet 2018).

This paper takes the example of the Green Revolution as a "natural experiment" of international diffusion of agricultural technology – namely, improved, high-yielding crop varieties – and investigates whether the diffusion of high yielding crop varieties for a number of crops led to the convergence of yields in the developing world to the yield frontier (i.e., the outer margin of production possibilities at a given point in time). The Green Revolution provides a unique case study for the study of agricultural technology diffusion, as it was an unprecedented public investment in agricultural research and development and the diffusion of genetic resources to developing countries (where this technology was almost entirely absent) by countries at or close to the technological frontier.

To investigate this research question – of whether this substantial investment in technology diffusion led to yield convergence in the developing world – 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) as well as other relevant factors such as country-level expenditure on agricultural research and development and intellectual property rights protection regimes. I further explore 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 contribute 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.

2. Related literature

This paper aims to investigate how the diffusion of improved genetic resources contributed to a reduction in yield gaps 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 impacts of the diffusion of modern high-yielding crop varieties in the developing world 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.

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. One of the first major investigations of the impacts of the Green Revolution comes from 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) 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 3-4% 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 modern variety diffusion 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.

This research contributes to these two streams of related literature on agricultural productivity growth (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) by disentangling the contribution of the diffusion of modern crop varieties to yield 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. Investigating the contributions of improved crop varieties to land and labor productivity in the developing world has the potential to stimulate discussion 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.

3. Hybrid technology and the diffusion of genetic resources

In addition to the broader discussion about the diffusion of genetic resources and agricultural productivity, this paper also aims to contribute to another more focused branch of literature addressing 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 and what are known as "genetic use restriction technologies" (GURTs), defined as "a range of molecular strategies designed to impede transgene movement" (Hills *et al.* 2007). These strategies are designed 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. As a result of this, private seed companies have an incentive to protect their investment in developing a new variety by finding ways to prevent farmers from continuing to re-plant their products without re-purchasing them.

There is thus an important trade-off between policies that incentivize innovation and investments into research and development in the plant breeding sector by restricting access to new plant varieties to those who have the means to purchase them, and policies that incentivize the diffusion of genetic resources. The so-called "terminator" technology – a form of gene regulation that prevents seeds sold by a company from producing new viable seed - is one of the most famous examples of a GURT (Hills *et al.* 2007). However, hybrid crop varieties also offer a form of technological control over diffusion, since they 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). Thus, hybrid crops are beneficial for private seed companies because the production of hybrid seed requires more specialized operations than the seed of open-pollinated varieties, and for this reason it is easier to appropriate the rents associated with breeding a more productive crop variety.

Goeschl and Swanson (2000) exploit the fact that commercial hybrid varieties are only available for certain crops (e.g., maize and sorghum) to investigate the impact of this "precursor" to the more advanced genetic use restriction technologies associated with biotechnology. By analyzing yield growth in eight crops in a panel of both developed and developing countries, they find that while yields in developing countries grow faster the greater the yield gap at the beginning of the overall period for six of the crops they consider, supporting yield convergence, they do not find evidence to support convergence for maize and sorghum, crops for which hybrid varieties were available and commercialized. In similar work, they project the impact that genetic use restriction technologies might have on diffusion in the future, and forecast that developing countries are likely to see reduced yield growth as a result of the spread of GURTs, with least developed countries being impacted the most, thus highlighting that factors that may improve the incentives for innovation and investment in research and development may also negatively impact the diffusion of new agricultural technologies such as hybrid seed (Goeschl and Swanson 2003).

More recently, utilizing detailed data on country-level intellectual property right regimes, Spielman and Ma (2016) also investigate the extent to which the hybridization and commercialization of crops (as well as varying levels of IPR) affects diffusion and yield convergence. They use a panel dataset of both developed and developing countries and include additionally a number of other variables coding for inputs such as agricultural labor, the use of machinery and fertilizer, and the area of land harvested per crop. They find that both biological (i.e. hybrid technology) and legal forms of intellectual property protection promote yield convergence, with effects varying across crops.

In this paper, I build upon and strengthen these past analyses by including variables for the key technology of the Green Revolution – improved, high-yielding seeds – and for country-level human capital and research and development expenditures, that may also impact the successful diffusion of genetic resources.

5. The context 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 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 these investments led to the creation of 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. These investments were made for a number of reasons related to both humanitarian objectives as well as geopolitical concerns associated with the Cold War, but regardless of the rationale for launching the Green Revolution, it nonetheless represents one of the greatest episodes of technological diffusion in history.

In this paper, I use this “natural experiment” to analyze the extent to which the technology itself (modern crop varieties) as well as a number of other factors (intellectual property rights regimes, national investments in R&D, other inputs such as fertilizer or labor) led or did not lead to convergence in crop yields towards the frontier across the developing world. In particular, this period offers an interesting episode for investigating the various contributions to crop-specific yield growth from the private and public sector, given that private-sector firms were not involved in the production of modern varieties in the majority of the developing world during most of the Green Revolution period, with the exception of those producing maize, sorghum, and millet hybrids (Evenson 2005).

6. Theoretical background

This paper's analysis is rooted in Hayami & Ruttan's theory of induced technical change, in which agricultural productivity growth is seen as being 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 – such as 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 focus on the "technology factor" then opens up the possibility of technology *transfer* – if economic growth in the agriculture sector is not solely driven by the accumulation of land and other forms of capital, but also by technology, then the diffusion of agricultural technology offers another path towards growth (and convergence). Indeed, from the Columbian exchange to the expeditions of American botanists to Iraq to collect date varieties for importation to Southern California in the early twentieth century, the diffusion of genetic resources has been a key source of transformation in agricultural activity and productivity throughout history.

The Green Revolution thus offers a unique episode for studying the impact of agricultural productivity growth driven by technology transfer, as an example of a case where countries at the productivity frontier – those which had already gone through the technological revolution associated with modern plant breeding – invested substantially in the adaptation and diffusion of modern varieties to developing countries, where this technology was almost entirely absent. The empirical approach of this paper is designed to assess the extent to which this diffusion of a novel agricultural technology (modern, high-yielding crop varieties) led to yield convergence among Green Revolution crops in the developing world, by exploiting panel data from Evenson and Gollin (2003b) on HYV adoption rates. 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).

7. Methodology

In this section, I first describe the data utilized and then the empirical approach taken – which includes both a production function analysis as well as the convergence analysis, which is the primary focus of the paper.

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. Some efforts have been 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.

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.

Empirical approach

My empirical analysis is rooted in a Cobb-Douglas production function, following the path of a number of seminar early papers such as Hayami and Ruttan (1970). I introduce a technology variable "A" representing the level of improved crop variety adoption, while L represents labor, T represents land, F represents fertilizer use, and K represents agricultural capital such as machinery and livestock):

$$\mathrm{Y} = \mathrm{A}\, L^{\alpha} T^{\beta} F^{\gamma} K^{1-\alpha-\beta-\gamma} \qquad (1)$$

I divide this equation by T (e.g. for land productivity) and take the natural log, giving:

$$\ln\left(\frac{Y}{T}\right) = \ln(\mathrm{A}) + \alpha\ln\left(\frac{\mathrm{L}}{T}\right) + \gamma\ln\left(\frac{\mathrm{F}}{T}\right) + (1-\alpha-\beta-\gamma)\ln\left(\frac{\mathrm{K}}{T}\right) \quad (2)$$

Analysis following from this transformation has been carried out using fixed effects (with country and time dummies) to control for the time-invariant characteristics of each country. I run the following regression for both land and labor productivity, where x_{it} represents a vector of other time-varying input variables at the country-level and the "Proportion modern varieties" variable represents the percentage (in 10% intervals) of modern varieties grown on the area planted to the given crop. I also include μ_i (country fixed effects) and λ_{t} (time fixed effects), while ε_{it} represents the time-varying unobservables that remain after the within transformation is carried out:

$$\ln(y)_{it} = \alpha_0 + x'_{\mathrm{it}} * \delta + \beta * Proportion\ modern\ varieties_{it} + \mu_i + \lambda_{\mathrm{t}} + \varepsilon_{it} \quad (3)$$

In addition, I also utilize 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 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), decomposing yield growth as follows:

$$G_{it} = c_i + \alpha_t + \beta G_{i,t-1} + \varphi * \Delta MV_{it} + \mu * \Delta MV_{it} * \Delta G_{i,t=0} + \gamma_j X_{it} + \varepsilon_{it} \quad (4)$$

This specification includes the lagged dependent variable $G_{i,t-1}$ as an explanatory variable, typical in linear dynamic panel data estimation, since the yield gap for a given crop in a country is highly dependent on its yield gap in the previous period. I include a term for the change in the adoption rate of the given crop in country i (ΔMV_{it}), an interaction between this adoption rate and the country's yield gap in the first period of the dataset ($\Delta MV_{it} * \Delta G_{i,t=0}$), and terms for a number of other variables including the change in the amount of fertilizer, machines, livestock and labor per hectare. In addition, country fixed effects and period dummies are included to control for country- and period-level unobservables. Additional regressions are included that extend this basic formulation to include other variables of interest such as research and development expenditures and country-level intellectual property right regimes.

8. Results

In this section, I present first an example of basic productivity function results (estimated using fixed effects for wheat) and then the results for the convergence analysis (estimated using a two-step Arellano-Bond GMM estimator), both by crop and in a pooled estimation.

Production function analysis

I first present an example set of regressions (using fixed effects) that provide results for a wheat production function (including technology, i.e. the adoption rate of modern, high-yielding varieties). I find in regression (1) that a change of 10% in the wheat area cultivated with modern varieties leads to about a 3% increase in yields. However, when I include an interaction between the proportion of cropland cultivated with wheat and the amount of fertilizer used per hectare, I find instead that it is the package of improved wheat variety use and fertilizer used together that leads to higher yields, not improved varieties on their own.

Table 1. Modern variety diffusion and wheat yields

Outcome var.: ln(wheat yield)	**(1)**	**(2)**	**(3)**
Ln (labor / land)	-0.163 (0.099)	-0.160 (0.098)	-0.186* (0.102)
Ln (fertilizer / land)	0.035 (0.025)	0.025 (0.026)	0.026 (0.026)
Ln (machinery / land)	0.032 (0.034)	0.023 (0.034)	0.030 (0.035)
Ln (livestock / land)	**0.246*** (0.084)**	**0.217** (0.085)**	**0.227** (0.087)**
Area planted	0.000* (0.000)	0.000* (0.000)	0.000* (0.000)
Wheat MV (10%)	**0.028*** (0.006)**	-0.008 (0.021)	-0.016 (0.027)
Wheat MV (10%) X Ln (Fert)		**0.010* (0.005)**	**0.010* (0.005)**
Proportion of MV (10%) x SSA			0.009 (0.044)
MV (10%) x Ln (Fert) x SSA			0.003 (0.014)
Constant	-0.173* (0.120)	-0.124*** (0.123)	-0.158*** (0.130)
	Country FE: Yes	Country FE: Yes	Country FE: Yes
	5-year FE: Yes	5-year FE: Yes	5-year FE: Yes
	No. of obs.: 420	No. of obs.: 420	No. of obs.: 420
	R-squared=0.825	R-squared=0.827	R-squared=0.827

[a] Note: *, **, and *** represent 10, 5 and 1% significance levels, respectively; standard errors in parentheses.

In (3), I include an interaction term for sub-Saharan countries to determine if these countries experience less of a positive yield impact from the diffusion of improved wheat varieties and the "package" of modern varieties and fertilizer used concurrently, but do not find these interaction terms to be significant. I also find the amount of livestock per hectare to be significant across all three variables. However, it should be noted that these estimates should not be considered to be causal, given that the fixed effects approach here does not control for time-varying unobservables, but rather just provides an example of a production function featuring the level of technology.

Convergence analysis – crop-specific estimations

I now present two tables containing crop-level regressions. The first investigates 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. The second table in this section includes an interaction between the change in the proportion of modern varieties cultivated and the amount of fertilizer used per hectare, since the Green Revolution is often portrayed as a "package" of modern, fertilizer-responsive varieties coupled with fertilizer. The dependent variable is the country-level and crop-specific yield gap, measured as the difference 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.

In Table 2, we can see that the variables capturing the change in the proportion of cropland cultivated with modern varieties are only significant for sorghum. Here, we can see that 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. 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 benefited more from adoption of modern sorghum varieties than did those that were originally farther from the sorghum yield frontier (i.e., that had larger yield gaps in the initial period of the dataset). Last, it can be observed that the diagnostic statistics for the maize regression indicate that the identification is too weak to provide insights into the effect of the main variables of interest on the yield gap.

Table 2. Arellano-Bond estimates for the evolution of the yield gap for wheat, rice, sorghum and maize[1]

Outcome variable:	Yield gap (wheat)	Yield gap (rice)	Yield gap (sorghum)	Yield gap (maize)
Yield gap, first lag	**1.048*** (0.071)**	**1.011*** (0.041)**	**0.987*** (0.036)**	**1.142*** (0.020)**
Δ Prop. MVs x Yield gap$_0$	0.300 (0.998)	0.146 (0.131)	**0.285** (0.112)**	-0.018 (0.082)
Δ Prop. MVs	-599.842 (32,249.040)	-7,367.698 (6,146.771)	**-8,402.240*** (3,135.317)**	850.161 (3,171.591)
Δ (labor / land)	16,534.710 (16,973.720)	2,083.189 (2,484.031)	337.984 (2,015.987)	1,330.307 (1,261.171)
Δ (fertilizer / land)	-51.914 (47.709)	26.366 (43.214)	-9.027 (14.610)	4.978 (15.747)
Δ (machinery / land)	515.232 (637.995)	-108.445 (153.477)	168.421 (120.381)	-163.232 (85.686)
Δ (livestock / land)	-304.137 (2,651.149)	-117.006 (1,267.812)	-2.950 (591.327)	-195.317 (354.522)
Δ (area planted)	-0.001 (0.001)	0.000 (0.000)	0.000 (0.000)	0.001 (0.000)
AR(1) p-stat	0.004	0.000	0.000	0.434
AR(2) p-stat	0.207	0.691	0.596	0.067
Hansen p-statistic	0.722	0.474	0.704	0.039
Number of countries	48	67	58	69
Number of observations	276	459	331	414
Number of instruments	43	59	29	**54**

[a] Note: *, **, and *** represent 10, 5 and 1% significance levels, respectively; standard errors in parentheses.

In Table 3, 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. This interaction is shown to be significant and negative for rice, indicating that concurrent increases in the adoption rate of high-yielding rice varieties and the use of fertilizer led to a reduction in the country's rice yield gap for that period. The results for sorghum are similar to the results shown in Table 2, with the positives changes in the adoption rate of modern sorghum varieties leading to greater yield convergence, while neither the change in fertilizer use variable or the fertilizer-modern variety interaction are shown to be significant. Again, as shown by the autocorrelation tests, the maize results are shown to not provide proper identification, and no interaction variables are shown to be significant for wheat.

It should be noted that the results for the wheat regression do not indicate that the diffusion of modern Green Revolution wheat varieties did not lead to *productivity* increases, just that this diffusion did not lead to *catching up* of developing country wheat yields to those at the technological frontier. An interpretation of this could be that while wheat is a major developed country crop in Europe and North America, thus leading to greater investments in wheat breeding, rice and sorghum are predominantly developing country crops, meaning that convergence is easier to achieve for these crops.

We can also note from the significant estimates for the first lag of the yield gap (the dependent variable) that the sorghum and rice yield gap tended to decrease for most developing countries in the sample (from the coefficient estimate below one), while the yield gap for wheat tended to increase over time for the set of countries in the sample.

Table 3. Arellano-Bond estimates for the evolution of the yield gap for wheat, rice, sorghum and maize – with fertilizer interaction[1]

Outcome variable:	Yield gap (wheat)	Yield gap (rice)	Yield gap (sorghum)	Yield gap (maize)
Yield gap, first lag	**1.049*** (0.073)**	**0.938*** (0.149)**	**0.992*** (0.053)**	**1.369*** (0.097)**
Δ Prop. MVs x Yield gap_0	-0.260 (0.805)	0.180 (0.313)	**0.210* (0.083)**	-0.016 (0.064)
Δ Prop. MVs x Δ (fert./land)	1,326.148 (1,925.255)	**-53.634* (16.184)**	-21.073 (45.458)	4.460 (27.536)
Δ Prop. MVs	1,359.250 (29,545.760)	-8,451.274 (14,697.410)	**-6,071.214** (3,272.471)**	641.345 (2,523.615)
Δ (labor / land)	-567.055 (11,520.820)	3,576.006 (3,413.570)	-26.407 (2,145.741)	43.780 (1,513.438)
Δ (fertilizer / land)	-172.526 (241.060)	-6.889 (15.855)	-18.992 (13.743)	10.053 (23.840)
Δ (machinery / land)	-154.278 (1,258.684)	-77.632 (91.409)	83.492 (109.254)	**-183.674* (98.322)**
Δ (livestock / land)	1,936.878 (1,720.880)	483.222 (2,204.023)	153.022 (843.966)	-121.207 (333.894)
Δ (area planted)	-0.000 (0.001)	0.000 (0.000)	**0.001* (0.001)**	0.000 (0.000)
AR(1) p-stat	0.004	0.003	0.001	0.444
AR(2) p-stat	0.226	0.722	0.673	0.068
Hansen p-statistic	0.996	0.736	0.999	0.179
Number of countries	48	67	58	69
Number of observations	276	459	331	414
Number of instruments	44	60	49	64

[a] Note: *, **, and *** represent 10, 5 and 1% significance levels, respectively; standard errors in parentheses.

Table 4. Arellano-Bond estimates for the evolution of the yield gap – pooled dataset[1]

Outcome variable:	Ln(yieldgap)
Yield gap, first lag	**1.036*** (0.064)**
Δ Prop. MVs	-0.117 (0.094)
Δ Prop. MVs x Yield gap_0	0.085 (0.105)
Δ Prop. MVs x Δ (fert./land)	0.001 (0.000)
Δ Prop. MVs x Hybrid	**0.262* (0.181)**
Δ Prop. MVs x IPR_{t-1}	**0.032** (0.013)**
Δ Prop. MVs x IPR_{t-1} x Hybrid	**-0.199** (0.086)**
Δ Prop. MVs x IPR_{t-1} x Hybrid x Yield gap_0	**0.216** (108)**
Hybrid x Yield gap_0	0.042 (0.051)
IPR_{t-1}	-0.001 (0.021)
Δ (labor / land)	-0.030 (0.047)
Δ (fertilizer / land)	-0.001 (315.832)
Δ (machinery / land)	0.002 (0.005)
Δ (livestock / land)	-0.004 (0.023)
Δ (area planted)	-0.000 (0.000)
AR(1) p-stat	0.000
AR(2) p-stat	0.343
Hansen p-statistic	0.239
Number of groups	184
Number of observations	1,073
Number of instruments	145

[a] Note: *, **, and *** represent 10, 5 and 1% significance levels, respectively; standard errors in parentheses.

In Table 4, I include 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 a hybrid crop (as is the case for maize and sorghum). The results show that 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 reduction in the associated yield gap for the developing country in question (for hybrid crops). On the other hand, if the crop was *not* easily commercializable as a hybrid, 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.[1] Additionally, a significant estimate for the interaction between the change in the modern variety adoption level for a crop and the first lag of the IPR level suggests that higher intellectual property protection had a *negative* impact on the creation and diffusion of improved non-hybrid varieties (but a *positive* impact on the creation and diffusion of hybrid varieties). Finally, 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 in terms of leading to reductions in the size of the yield gap is greater for countries that were not far from the frontier at the beginning of the panel.

An interpretation of these results is that greater levels of 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 – 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 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

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

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 from innovating to a greater extent in the development and sale of improved rice and wheat varieties in the absence of a technological form of protection for their investment.

In Table 5, I include terms interacted with a variable that provides 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 adding this variable is to capture any potential impacts of country-level R&D spending in the agriculture sector taking place, for example, in the country's national agricultural research center (in addition to R&D taking place in the country's private seed sector). The innovation driving the Green Revolution took place not just in international agricultural research centers (IARCs) such as the International Rice Research Institute and the International Maize and Wheat Improvement Center, but also importantly at a country-level through national agricultural research systems that worked to adapt modern varieties received from IARCs to local conditions. I include interactions between the first lag of R&D expenditures and whether or not the crop was readily commercializable as a hybrid (i.e., either maize or sorghum); the intellectual property rights regime of the country in the previous period; the change in the adoption rate for the given crop; and with the previous interaction between the change in adoption rate, the "hybrid" dummy, and the lagged IPR regime.

Table 5. Arellano-Bond estimates for the evolution of the yield gap – pooled dataset with R&D[1]

Outcome variable:	Ln(yieldgap)
Yield gap, first lag	**0.989*** (0.077)**
Δ Prop. MVs	-0.103 (0.083)
Δ Prop. MVs x Yield gap_0	0.080 (0.089)
Δ Prop. MVs x Δ (fert./land)	0.001 (0.001)
Δ Prop. MVs x Hybrid	**-0.236* (0.128)**
Δ Prop. MVs x IPR_{t-1},	**0.029** (0.013)**
Δ Prop. MVs x IPR_{t-1} x Hybrid	0.108 (0.074)
Δ Prop. MVs x IPR_{t-1} x Hybrid x ln(R&D $exp)_{t-1}$	**-0.088** (0.043)**
Δ Prop. MVs x ln(R&D $exp)_{t-1}$	-0.001 (0.005)
IPR_{t-1}	0.001 (0.016)
ln(R&D $exp)_{t-1}$	-0.007 (0.007)
ln(R&D $exp)_{t-1}$ x Hybrid	**-0.019* (0.010)**
Δ (labor / land)	-0.020 (0.042)
Δ (fertilizer / land)	-0.001 (0.001)
Δ (machinery / land)	-0.001 (0.003)
Δ (livestock / land)	-0.001 (0.015)
Δ (area planted)	-0.000 (0.000)
AR(1) p-stat	0.000
AR(2) p-stat	0.283
Hansen p-statistic	0.773
Number of groups	184
Number of observations	1,073
Number of instruments	172

[a] Note: *, **, and *** represent 10, 5 and 1% significance levels, respectively; standard errors in parentheses.

I present several interesting findings as a result of this estimation. I find that investments in agricultural research and development in the previous period contribute to yield convergence for hybrid crops with the presence of stronger IPR protection in the previous period, and when coupled with higher adoption of modern varieties. Additionally, greater investment in agricultural R&D in the previous period is found to lead to increased yield convergence, but only for hybrid crops (regardless of the level of IPR protection in the previous period). And, as before, I 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.

9. Conclusion

In this paper, I analyze how increases in adoption rates of modern varieties of four crops during the Green Revolution period led or did not lead to yield convergence in a number of developing countries. I find evidence that an increase in the "package" of fertilizer use and the cultivation of modern rice varieties contributed significantly to yield convergence for rice. In addition, I also find that greater adoption of modern Green Revolution sorghum varieties led to substantial decreases in developing country yield gaps, but to a greater extent for countries that were originally closer to the sorghum yield frontier, providing some evidence of a "low productivity trap" for the crop.

I further 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 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. However, this effect is 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. Last, I find that country-level research and development expenditures in the previous period coupled with higher IPR protection supported greater yield convergence for hybrid crops when coupled with higher adoption of modern varieties; and that R&D expenditures for maize and sorghum contributed to yield convergence of developing countries regardless of the diffusion of modern varieties or the level of IPR protection.

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). 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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