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Private Sector Incentives and the Diffusion of Agricultural Technology: Evidence from Developing Countries

DAVID J. SPIELMAN & XINGLIANG MA
Environment and Production Technology Division, International Food Policy Research Institute, Washington, DC, USA

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ABSTRACT *The role of intellectual property rights (IPRs) has been extensively debated in the literature on technology transfers and agricultural productivity growth in developing countries. However, few studies offer cross-country evidence on how IPRs affect yield growth by incentivising private sector investment in cultivar improvement. We address this knowledge gap by testing technology diffusion patterns for six major crops using a unique dataset for the period 1961–2010 and an Arellano–Bond linear dynamic panel-data estimation approach. Findings indicate that biological and legal forms of IPRs promote yield gap convergence between developed and developing countries, although effects vary by crop.*

1. Introduction

The expansive literature on agricultural development provides strong grounding for the argument that technological change is a key driver of productivity improvement, economic growth, and poverty reduction (Binswanger & Von Braun, 1991; Hayami & Ruttan, 1971; Johnston & Mellor, 1961; Schultz, 1968). The empirical evidence largely supports this argument (for example, Fan, 2000; Fan, Hazell, & Thorat, 2000; Fan & Pardey, 1997). A strong argument can also be made that economic policy incentives encourage investment in the agricultural research and development (R&D) that underpins technological change (Alston, Norton, & Pardey, 1995, 1999; Evenson & Kislev, 1973) and technology adoption by farmers (Feder, Just, & Zilberman, 1985; Lipton & Longhurst, 1989). This is particularly relevant for improving cultivars for major food staple crops. According to estimates from Evenson and Gollin (2003), improvements in such crops account for 20–50 per cent of yield growth in developing countries between 1960 and 2000.

However, since the 1970s, the study of innovation incentives in developing-country agriculture has focused primarily on the contribution of public research and extension systems (see, for example, Alston, Chan-Kang, Marra, Pardey, & Wyatt, 2000). Only in the last two decades have incentives for private investment in the research, development, and delivery of new agricultural technologies become a topic of significant discussion (Naseem, Spielman, & Omamo, 2010). This follows not only the successful commercialisation of emerging scientific advances (for example genetic engineering, genomics, and informatics) led by the private sector but also slow growth in public R&D expenditures and limited scientific output from public research organisations in many

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Correspondence Address: David J. Spielman, International Food Policy Research Institute, 2033 K St. NW, Washington, DC, USA. Email: d.spielman@cgiar.org

An Online Appendix is available for this article which can be accessed through the online version of this journal available at http://dx.doi.org/10.1080/00220388.2015.1081171 low-income developing countries (Beintema, Stads, Fuglie, & Heisey, 2012; Byerlee, Alex, & Echeverría, 2002; Pardey & Beintema, 2001; Pray, 1992). As a result, many scholars predict greater reliance on private R&D investment in developing-country agriculture and thus on private R&D incentives such as intellectual property rights (IPRs) (Byerlee & Fischer, 2002; Pingali & Traxler, 2002; Spielman, 2007).

In broad terms, theory suggests that when IPRs enable developed-country innovators to profitably transfer technologies to developing countries – and when developing-country innovators imitate, adapt, and improve these innovations – then IPRs can contribute to technological change, economic growth, and welfare improvement in the developing world. Much conceptual and empirical evidence supports this argument (Kanwar & Evenson, 2003; Lai, 1998; Lesser, 2000; Taylor, 1993, 1994), but a significant body of theory and evidence also reveals its complex nuances (Chin & Grossman, 1990; Deardorff, 1992; Helpman, 1993).

This argument over IPRs also extends to the agricultural sector. IPRs can encourage private investment in developing new cultivars, genetically modified crops, livestock vaccines, crop protection chemicals, and other inputs that, in turn, can enhance agricultural productivity, foster agricultural development, and reduce poverty (Eaton, Tripp, & Louwaars, 2006; Lesser, Horstkotte-Wesseler, Lele, & Byerlee, 2000; Lipton & Longhurst, 1989; Pray, 1992). However, IPRs can also provide private firms with temporary monopolies of a welfare-reducing nature which may limit small-scale, resource-poor farmers' access to technological solutions that increase on-farm productivity, improve household food security, and reduce poverty (Goeschl & Swanson, 2000; Srinivasan & Thirtle, 2000). Alternatively, IPRs simply may not matter to developing-country agriculture because firms with significant intellectual property portfolios – typically, multinational crop science firms – rarely seek IPR protection for their technologies in developing countries, thus giving developing-country researchers and farmers unimpeded freedom to operate (Binenbaum, Nottenburg, Pardey, Wright, & Zambrano, 2003).

Empirical evidence of IPRs' contribution to agricultural productivity growth is mixed. Several studies suggest that the United States' Plant Variety Protection Act of 1970 boosted cotton and wheat yield growth rates (Kolady & Lesser, 2009; Naseem, Oehmke, & Schimmelpfennig, 2005; Perrin, Kunnings, & Ihnen, 1983), although confounding evidence was found for wheat and tobacco yields (Alston & Venner, 2000; Babcock & Foster, 1991). Similarly positive evidence for canola and wheat yields from Canada's Plant Breeders Rights Act of 1990 also exists (Carew & Devadoss, 2003; Carew, Smith, & Grant, 2009). For developing-country agriculture, however, the evidence is largely ambiguous (Naseem et al., 2010).

This paper explores the extent to which IPRs promote yield growth by encouraging the transfer of productivity-enhancing technologies from developed to developing countries. It extends Goeschl and Swanson's (2000) work on how strong forms of IPR protection limit the spread of productivity-enhancing technology from developed to developing countries. Their study, based on cross-country data from 1961 to 1991 for eight widely cultivated crops, indicates significant convergence in yield growth rates between developed and developing countries ('yield gap convergence') but also significant impediments to convergence that are attributable to country-specific structural characteristics or crop-specific technological characteristics. The impediments associated with country-specific characteristics are readily explained by fundamental differences in agroecological, historical, political, and geographic features between countries (see, for example, Fulginiti, Perrin, & Yu, 2004). Impediments associated with crop-specific characteristics, however, are mainly attributed by Goeschl and Swanson (2000) to economic incentives associated with the nature of the reproductive biology of individual crops. In particular, they attribute slower rates of yield gap convergence to hybridisation, a biological form of IPR that is explained in detail later.

What the Goeschl and Swanson (2000) study lacks, however, is an explanation of other, more institutional constraints to yield gaps convergence. Specifically, their study does not fully address the role of legal forms of IPRs such as plant variety protection laws or other policies and regulations designed to encourage technology transfers and commercial activity related to cultivar improvement.

Thus, this paper provides a more complete exploration of biological *and* legal IPRs across a large set of developing countries using a model that decomposes crop-specific movements toward yield gap convergence.

The next section offers a conceptual discussion that ties together technology diffusion, private sector innovation incentives, and agricultural productivity growth in developing countries. Section 3 sets forth an empirical specification, followed by details on data and data sources in Section 4. Section 5 discusses results, followed by concluding remarks in Section 6.

2. A Conceptual Model of Technology Diffusion and Private Sector Incentives

Studies of the impact of technology transfers on growth rate convergence are often examined in the context of endogenous growth theory (Mankiw, Romer, & Weil, 1992; Romer, 1994). In the broadest terms, these models posit that a developing country's growth rate tends to converge with that of a developed country through the transfer of technologies from the frontier (represented by the state of innovation in the developed country), assuming that innovators in the former country can adapt, imitate, and apply these technologies at a lower cost in their own economy. As a result of this process, developing countries tend to grow more quickly by catching up – the 'advantages of backwardness' described by Gerschenkron (1962) – and converge in the long run with the same steady-state rate of growth of developed countries.

Schumpeterian models of endogenous growth such as that posited by Aghion and Howitt (2005) demonstrate that growth rate convergence is achieved in countries in which the conditions that enable innovation ensure a constant intensity of innovation. This suggests that long-run growth convergence generally depends on two necessary conditions: the innovators' ability to transfer technologies across countries and their ability to appropriate a portion of the rents accruing from the use of these technologies. Such conditions are met when the countries invest effectively in education and research (Aghion & Howitt, 2005), and when technology transfers are unconstrained by issues of technological adaptability (Acemoglu and Zilibotti, 2001; Basu & Weil, 1998), imperfect financial markets (Aghion, Howitt, & Mayer-Foulkes, 2005), special interests in the political economy (Parente & Prescott, 1994, 1999), and institutions that inhibit such transfers (Acemoglu, Aghion, & Zilibotti, 2002). Specifically, Aghion and Howitt (2005) and Aghion et al. (2005) demonstrate that country i's expected distance from the global technology frontier, defined as $\hat{d}_{i,t} \equiv \ln\left(\frac{\bar{A}_t}{A_{i,t}}\right)$, evolves according to:

$$\hat{d}_{i,t} = (1 - \mu_i)\hat{d}_{i,t-1} + (\bar{\mu} - \mu_i)\ln\gamma_i,$$

where $\bar{A}_t$ denotes the global productivity frontier, $A_{i,t}$ is the productivity of country i at time t, $\bar{\mu}$ is the global innovation rate, μ_i is the innovation rate of country i, and γ_i is the size or extent of the innovation in country i. If $\mu_i > 0$, then the long-run expected growth rate of country i will converge to the global productivity frontier growth rate. If $\mu_i = 0$, then this growth rate will lag behind the global frontier.

Empirical studies focus on the determinants in variation in convergence rates. For example, Madsen and Timol (2011) examine growth rate convergence using measures of total factor productivity (TFP) and labour productivity growth in the manufacturing sector in 19 industrialised countries between 1870 and 2006. Their results suggest that domestic R&D, international R&D spillovers, and financial sector development have driven convergence trends during this period, consistent with the Aghion and Howitt (2005) model. In one of the few applications of this model to agriculture, Trueblood and Arnade (2001) similarly draw on endogenous growth theory to test for crop yield convergence in Russia and the newly independent states carved out of the Soviet Union in 1991. Their results suggest that yield convergence between 1961 and 1998 was significantly constrained by insufficient investment in human capital formation through agricultural research and extension.

These studies provide the conceptual basis for this paper. In the context of developing-country agriculture, the underlying intuition of these models – the underlying dynamics of innovation, institutions, and technology transfers – can be extended to examine the transfer of yield-enhancing technologies from developed to developing countries. The fundamental idea is the same: such technologies can be transferred from developed countries and imitated by developing countries through adaptive research. The transfer and adaptation of cultivar improvements, a specific form of technology, has been central to the narrative on agricultural productivity growth and food security since the 1960s (Evenson & Gollin, 2003; Lipton with Longhurst, 1989). Such transfers are hypothesised to encourage the convergence of yield growth rates between developed and developing countries (Esposti, 2011; Goeschl & Swanson, 2000).

Necessarily, there are limitations to extending a macroeconomic growth model to an agricultural yield growth model.[1] First, there is no theoretical basis to the notion that yields *should* necessarily converge across countries over time (Sumberg, 2012). Nonetheless, an extensive body of evidence examines the role of technology transfers in closing yield gaps, both from the perspective of economics policy (Beddow, Pardey, & Alston, 2009; Evenson & Gollin, 2003; Evenson & Kislev, 1973) and the biophysical sciences (Van Ittersum et al., 2013; Van Wart, Kersebaum, Peng, Milner, & Cassman, 2013). Yield-based measures can also say much about the impact of food security policies – including policies on R&D and technology transfers that encourage productivity improvements – on the supply of food and the economic welfare of households in developing countries (Fischer, Byerlee, & Edmeades, 2014).

A second limitation is that yield growth rates are only partial measures of productivity growth: they capture changes in land productivity but not changes in capital or labour productivity. Measures of TFP are better at capturing growth that is attributable to overall improvements in how factors are combined in production (Coelli, Rao, & Battese, 1998; Fuglie, 2012; Headey, Alauddin, & Rao, 2010; Nin, Arndt, Hertel, & Preckel, 2003). As such, TFP measures are more appropriate to the study of yield growth-rate convergence between countries. However, no global mechanism currently collects, analyses, and shares long-term, crop-specific TFP trend data by country, forcing researchers to often rely on yield data for cross-country analyses of productivity growth in agriculture (for example, Fischer et al., 2014). Moreover, if it is assumed that the growth rate of capital and labour productivity are relatively constant over time (as may be the case in developing countries), then the yield growth rate may be closely correlated with the growth rate of TFP, with yield gaps thus explained by differences in initial conditions and other variables that are the focus of this study (Antle & Capalbo, 1988; see Online Appendix A; Hayami & Ruttan, 1971). In short, yield growth can be a useful measure of overall productivity growth under limited circumstances and when the contribution of technology and other determinants of productivity growth are cautiously interpreted.

With this in mind, we develop a conceptual model that considers yield gap convergence and the effect of both the state of technology and the institutions that influence technology transfers. We begin with the hypothesis that impediments to yield gap convergence associated with crop-specific characteristics hinge on the economic incentives that result from differences in the reproductive biology of individual crops. Specifically, we follow on work by Goeschl and Swanson (2000), who distinguish between hybrid crops, on the one hand, and open/self-pollinating crops, on the other hand, in explaining yield growth convergence. Hybrid crops are characterised by their unique ability to exhibit heterosis, or an increase in yield or vigour that results from genetic contributions derived from crossing distinct parental lines. The economic value of hybrids lies in the fact that yield gains conferred by heterosis decline dramatically after the first generation of seed is sown, thus compelling farmers to purchase new seed each season and providing innovators with a means of appropriating the gains from their R&D investment. This attribute contrasts with open/self-pollinated crops, for which harvested grains can be stored and used as seeds in the following year without significant loss of vigour and without remuneration to the innovator. Findings from Goeschl and Swanson (2000) suggest that yield enhancements embodied in hybrid crops diffuse less rapidly than enhancements embodied in open/self-pollinating crops, implying that the *biological* IPRs conferred by hybridisation to developed-country innovators make it prohibitively costly for innovators in developing countries to imitate these technologies and for resource-poor farmers to purchase them in the form of hybrid seed.[2]

In fact, there is much empirical evidence to show that technology flows for hybrid crops have contributed significantly to yield growth in developing countries; for example, for maize in Kenya, Malawi, Zambia, and Zimbabwe (Smale & Jayne, 2010), and cotton, pearl millet, and sorghum in India (Gruere & Sun, 2012; Pray & Nagarajan, 2010), rice in China (Li, Xin, & Yuan, 2010), and maize throughout Asia (Gerpacio, 2003). However, in all cases, the introduction of hybrids was accompanied by some policy or institutional change that created some related economic incentives for private firms to develop and market hybrids. These changes include public policies that encourage commercial activity in the country's seed sector, or *legal* forms of IPRs such as plant variety protection certificates. For example, the contribution of hybrids to yield growth in India mentioned above was largely contingent on policy reforms that began in the late 1980s and encouraged international technology flows, private-sector innovation, and private investment in the seed industry (Kolady, Spielman, & Cavalieri, 2012; Pray, 1992; Ramaswami, 2002). This suggests that policy reforms and legal IPRs can give innovators a means of appropriating the gains from their R&D investment in a manner similar to biological IPRs, and can thus affect the costs of technology facing both innovators and farmers in developing countries.

Apart from technology transfers resulting from improvements in innovation incentives and biological and legal IPRs, other possible explanations for yield growth exist. On the supply side, transfers of non-appropriable, public-goods knowledge such as new practices for managing crops, water, and soil nutrients may contribute to yield growth. On the demand side, growth in domestic and export market size and market value may similarly encourage farmers to invest in yield improvement. But even in the presence of such effects, the extent to which IPRs affect yield growth and movements toward yield growth convergence between developed and developing countries remains an interesting empirical question.

3. An Empirical Model

To test whether IPRs influence the rate of yield gap convergence between developing (technological follower) and developed (technological leader) countries for a given crop, we specify the empirical model as follows:

$$G_{it} = c_i + \beta G_{i,t-1} + \alpha G_{i,t_0} + \sum_{j=1}^{4} \gamma_j \Delta X_{i,j} + \sum_{j=1}^{3} \theta_j \Delta IPR_{i,t-j-1} + \varepsilon_{it}, \quad (1)$$

where G_{it} denotes the gap in yield growth rates between the leader country and the follower country i at time t for the given crop (see Online Appendix B), and G_{i,t_0} is the gap under initial conditions. ΔX_i is the change of a vector of agricultural inputs including agricultural labour, harvested area, machinery, and fertiliser. The term ΔIPR_i denotes the change in the IPR regime of country i over time. $\alpha, \beta, \gamma, \theta$ are model parameters to be estimated. The term G_{it} can be more accurately defined as:

$$G_{it} = \frac{Y_t^* - Y_{t-1}^*}{Y_{t-1}^*} - \frac{Y_{it} - Y_{i,t-1}}{Y_{i,t-1}} = \frac{Y_t^*}{Y_{t-1}^*} - \frac{Y_{it}}{Y_{i,t-1}}, \quad (2)$$

where Y_{it} is the yield of country i in time t, and Y_t^* is the yield in the leader country in the same time period.

In Equation (1), the intercept term c_i captures country-specific, time-invariant structural factors in follower country i, for example agroclimatic conditions, geographic distance from the leader country, traditional crop-management practices, or other factors that uniquely contribute to the yield gap between the leader country and the follower country. The coefficient β captures the overall rate of technology diffusion between the leader and follower country over time, effectively measuring the magnitude by which the yield gap in the current time period is related to the yield gap in the previous period. The coefficient α captures the extent to which the current yield gap is affected by the gap in initial conditions, effectively testing for backwards advantage or a 'catching-up effect'; that is, the notion that the further a country is from the technological frontier in the initial time period, the lower the imitation cost and therefore the faster it will catch up to the technology frontier.

The coefficient γ denotes the effect on yield gaps associated with the rate of agricultural intensification as well as extensification. Hayami and Ruttan (1971) show that yield may be strongly affected by agricultural intensification, especially changes in the labour–land ratio, the use of farm machinery, fertiliser, and other inputs.[3] Relatedly, yield may be affected by changes in cultivated area ($\Delta Area_{it}$), as land-use expansion tends to push crop production into increasingly marginal land, and is thus likely to be associated with a decrease in the yield growth rate.

The coefficient Θ_1 denotes the effect of changes in country i's IPR regime strength (ΔIPR_{it}) at time t on yield gap convergence. We introduce a two-period lag effect (denoted $\Delta IPR_{i,t-1}$ and $\Delta IPR_{i,t-2}$) to capture the time required for a change of IPR regime to take effect in a given country and incentivise changes in firm behaviour. Each lag period represents a five-year increment, so the empirical model captures the IPR regime change effects in the current time period, after five years, and after 10 years. These lags are consistent with plant breeding timelines ranging from fast-tracked importation of broadly-adapted varieties that can be released quickly in a given country to slower processes that require investments in adaptive breeding and regulatory testing (Gisselquist & Jean-Marie, 2000; Gisselquist & Srivastava, 1997; McMullen, 1987).

3.1. Decomposition of Factors Affecting Yield Gap Convergence

Equation (1) allows for decomposition of changes in the yield gap for a given crop in country i into four distinct components – technological, production, institutional, and structural components – based on the notion that each component affects the flow of yield-enhancing technologies from leader countries to follower countries.

The 'technological component' refers to productivity-enhancing effects associated with the transfer of agricultural technologies that originate in developed countries and move to developing countries. By allowing y to denote the log value of yield Y, we can rearrange the yield gap term and express it more intuitively as $G_{it} = \Delta y_t^* - \Delta y_{it}$, where Δ signifies the change in the yield growth rate.[4] Assuming a positive initial yield gap, relative yield gains in country i are, over time, represented by a *decrease* in the gap toward convergence. Rearranging Equation (1) algebraically obtains:

$$\Delta y_{it} = \Delta y_t^* - c_i - \beta G_{i,t-1} - \alpha G_{i,t_0} - \sum_{j=1}^{4} \gamma_j \Delta X_{i,j} - \sum_{j=1}^{3} \theta_j \Delta IPR_{i,t-j-1} - \varepsilon_{it}, \tag{3}$$

which states that yield gains in country i (Δy_{it}) are determined by yield gains occurring in the leader country (Δy_t^*); time-invariant, county-specific characteristics of the follower country (c_i); the lagged gap in yield growth rates ($G_{i,t-1}$) and the initial gap (G_{i,t_0}); country-specific growth effects associated with agricultural production (ΔX); and changes in the IPR regime strength (ΔIPR_{it}). Table 1 summarises the expected coefficient signs and their interpretations.

The relationship between technological innovation and relative yield gains enters Equation (1) through two separate terms: yield growth in the leader country (Δy_t^*) and the gap between the leader and the follower countries ($G_{i,t-1}$). The first term represents an exogenous, yield-enhancing change in the technological state at the 'frontier' for a given crop that potentially carries over to all follower countries. The second term captures the diffusion of yield gains from the frontier to followers. The extent and rate at which diffusion occurs is captured by β. In this context, β is an estimate of the

Table 1. Interpretation of coefficient estimates

Coefficient	Sign and magnitude	Interpretation
c_i	$c_i > 0$	Agroecology is unfavourable to yield gap convergence
c_i	$c_i < 0$	Agroecologic conditions are favourable to yield gap convergence
β	$\beta < 1$	Yield gap convergence in which a smaller value indicates a more rapid convergence rate
β	$\beta \geq 1$	Yield gap divergence
α	$\alpha < 0$	Catching-up effect
α	$\alpha \geq 0$	No catching-up effect
$\gamma_1, \gamma_2, \gamma_3, \gamma_4$	$\gamma_1, \gamma_2, \gamma_3, \gamma_4 < 0$	An increase of agricultural labour, harvested area, machinery, or fertiliser increases yield gap convergence
$\gamma_1, \gamma_2, \gamma_3, \gamma_4$	$\gamma_1, \gamma_2, \gamma_3, \gamma_4 \geq 0$	An increase of agricultural labor, harvested area, machinery, or fertiliser does not increase yield gap convergence
$\theta_1, \theta_2, \theta_3$	$\theta_1, \theta_2, \theta_3 > 0$	Legal IPRs constrain imitation
$\theta_1, \theta_2, \theta_3$	$\theta_1, \theta_2, \theta_3 < 0$	Legal IPRs incentivise imitation
$\theta_1, \theta_2, \theta_3$	$\theta_1, \theta_2, \theta_3 = 0$	Legal IPRs do not affect imitation

constraint imposed on diffusion, and reflects the fact that technologies do not necessarily diffuse from the frontier to follower countries unimpeded because of certain characteristics of the crop and the technologies associated with its cultivation.

The sign and magnitude of coefficient β are essential elements of this model, and can be explained as follows. First, to demonstrate that developing countries are converging to the yield growth rate of the leader country, the diffusion rate β must satisfy the condition $|\beta| < 1$. Second, the closer the absolute value of β is to zero, the faster the diffusion rate. Third, if the absolute value of β is greater than 1, then yield growth rates in follower countries are falling behind those of the leader country. Fourth, if the (non-absolute) value of β is negative, then yield growth rates in follower countries are catching up rapidly, such that yield growth rates may actually exceed those of the leader country on occasion, thereby accelerating the convergence process.

Figure 1 simulates the different convergence trajectories with different values of β. Assuming a constant growth rate of 1 per cent in the leader country and an initial gap of 0.8 per cent, the left-hand figure shows the trajectories when β is positive and the right-hand figure shows the trajectories when β is negative. For $|\beta| = 0.1, 0.5, 0.8$, all the trajectories show convergence after certain time periods, but follower countries catch up fastest when the absolute value of β is smallest, for example, when $|\beta| = 0.1$.

The 'production component' refers to the productivity-related effects of a growth in agricultural input use in the follower country or the productivity-depressing effects when crop production expands to inferior land. This effect is captured by the change in aggregate agricultural inputs such as labour, machinery, and fertiliser for follower i and a term measuring the change in harvested area. We expect that agricultural input intensification (for example, an increase in the labour–land ratio or the use of machinery and fertiliser) will promote yield growth and therefore contribute to reducing the yield gap. This implies that the expected signs on the coefficients for agricultural labour, machinery, and fertiliser will be negative. Relatedly, the expected coefficient sign for harvested area is likely to be positive if extensification results in cultivation of increasingly marginal land.

The 'institutional component' refers to the productivity-enhancing effects of an institutional (that is, policy) regime that encourages innovation. This effect is captured by a term measuring changes in the IPR regime strength for follower country i. The degree to which changes in the IPR regime of country i encourage or impede yield enhancement, measured by a change in the yield gap, is reflected by the coefficient θ. A coefficient θ that is greater than zero implies that an increase in IPR regime strength is associated with an increase in the yield gap. This may be interpreted as an institutional barrier to yield-enhancing technological diffusion. A coefficient θ of less than zero implies that an increase in IPR regime strength is associated with a decrease in the yield gap, or an institutional incentive to

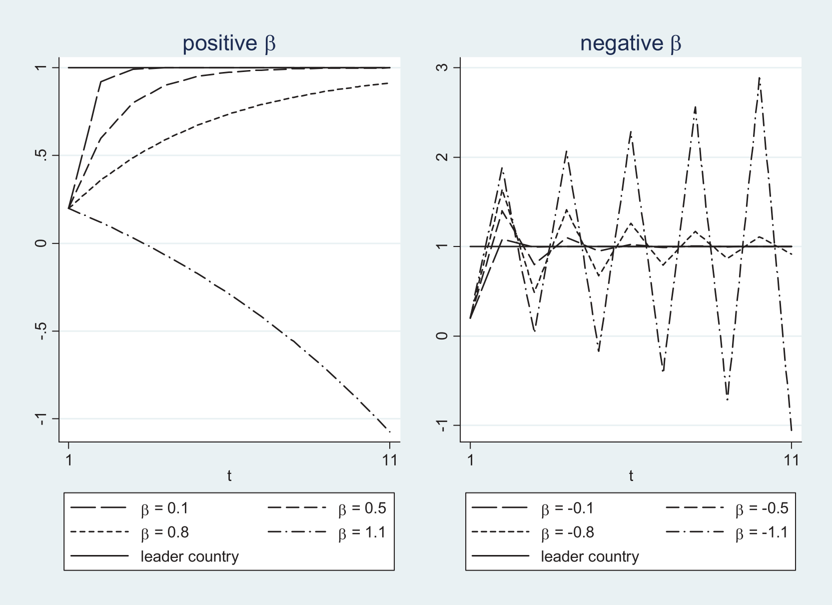

Figure 1. Simulations of crop yield convergence rates.
Note: These simulations assume a constant growth rate for the leader country and an initial yield gap of 0.8 for the follower country.

yield-enhancing technological diffusion. Alternatively, the coefficient may be interpreted as the extent to which an IPR regime signals innovators that rents from their innovations are appropriable in country *i*.

The 'agroecological component' captures other conditions in country *i* that affect the success of yield-enhancing technologies imitated by the follower country, and is represented by the time-invariant, country-specific intercept term c_i (explained earlier). In addition to agroecological differences between countries, this component may also capture certain institutional factors, for example rural education systems, historical path dependencies, and political regimes.

3.2 Estimation

Because the lagged dependent variable $G_{i,t-1}$ appears in Equation (1) as an explanatory variable, the estimation model violates the strict exogeneity assumption; that is, the idiosyncratic error in the current time period will be correlated with the explanatory variables in the past. It is thus impossible to apply the standard random or fixed effects panel data estimation techniques that rely on this assumption to estimate a model with an unobserved individual effect (Wooldridge, 2010; see Online Appendix C). This also rules out the possibility of ordinary least square (OLS) estimation. To remedy this, we apply a linear dynamic panel data estimation developed by Arellano and Bond (1991). The Arellano–Bond model utilises a generalised method of moments (GMM) framework by using further lagged values of the explanatory variables as instruments and resolves the correlation of the idiosyncratic error by using an efficient weighting matrix, therefore yielding consistent and efficient estimators (Wooldridge, 2010).

We estimate a country fixed-effects specification of the Arellano–Bond model with a balanced panel of cross-country data for the period 1961–2010. The fixed effects estimation cancels out the time-invariant, country-specific intercept term c_i while generating estimates for all other coefficients. To account for the paucity of countries producing some crops in our data, we restrict the number of lags to be used as instruments.

4. Data and Data Sources

Data on crop yields are taken from the Food and Agriculture Organization of the United Nation's online database (FAOSTAT) for the period 1961–2010 for a set of major food crops (Food and Agriculture Organization of the United Nations, 2013). Yield gaps for each crop are calculated as the difference between the yield growth rate for crop *n* in developing country *i* in time period *t* and the yield growth rate in the leader country for the same crop and the same time period, with the initial gap G_{i,t_0} defined as the gap in 1961. Across the period 1961–2010, this yield gap variable is generally greater than zero, indicating a decreasing level of yield inferiority (that is, increasing movement toward yield gap convergence) between developing and leader countries (Figure 2).

The 'leader country' is a composite of countries reporting the highest yields for each crop based on data from FAO (2013) (Table 2). In some cases, countries included in the composite are easily recognisable as global leaders in production and R&D for the specific crop, for example the United States with respect to cotton. In other cases, however, countries included in the composite are not obvious, for example Egypt with respect to rice. To the extent possible, we omitted the most obvious outliers (for example, the Democratic People's Republic of Korea with respect to millet), but resort to a set selection rule for designating the country leader. Specifically, we define the leader country as a fixed group of five countries that report the highest average annual yields between 1961 and 2010 (Table 2). We then use the average yields in five-year increments from all five countries to calculate the yield gap. This allows for calculation of a credible leader-country variable while minimising any effects caused by single-country idiosyncrasies in the yield data. However, the selection rule does not necessarily remove less-than-credible FAO data points that are evident in Table 2. Sensitivity analysis using alternative compositions of the leader country (discussed later) are inconsequential to our estimations.

As shown in Table 2, the total number of developing countries used in the subsequent crop-specific estimations ranges from 28 in the case of soybean to 74 in the case of maize. Table 2 also shows the average yield for each crop in the leader country composite and across all developing countries included in the sample. For most crops, the developing-country average yields are less than half of the

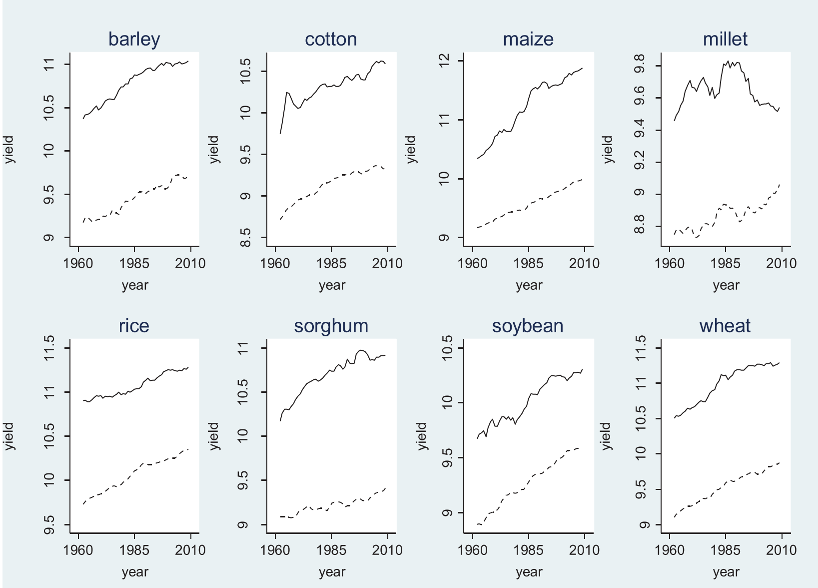

Figure 2. Crop yields in leader and follower countries, 1961–2010 (log hg/ha).
Note: The upper solid line shows the crop yield in the leader country in 1961–2010. The lower dashed line shows the average crop yield among follower countries in our sample in 1961–2010.

Table 2. Crops, yields, yield gaps, and leader countries

Crop	Average yield in leader countries (hg/ha)	Average yield in developing countries (hg/ha)	Leader countries	No. sampled follower countries
Barley	49,603	15,345	Ireland, The Netherlands, Zimbabwe, Switzerland, France	30
Cotton	30,703	11,867	Israel, Australia, Botswana, Guatemala, Syria	53
Maize	83,960	18,279	New Zealand, Israel, Jordan, Switzerland, Greece	74
Millet	15,552	8,031	Spain, Kenya, Hungary, China, Japan	38
Rice	64,970	27,154	Australia, Egypt, Spain, Japan, South Korea	68
Sorghum	44,820	12,852	Italy, France, Egypt, Israel, Spain	51
Soybean	22,936	12,286	Italy, Canada, Turkey, United States, Paraguay	28
Wheat	61,455	16,755	Netherlands, Ireland, United Kingdom, Denmark, France	42

Source: Authors.

Table 3. Summary statistics

Variable	Variable explanation	Mean	Std. dev.	Min	Max
Gap_lag	Lagged value of yield gap	0.023	0.231	−1.441	1.254
ΔLabour	Change in agricultural labour	0.037	0.080	−0.228	0.354
ΔArea	Change in harvested area	0.045	0.479	−2.789	6.081
ΔMachinery	Change in use of machinery	0.214	0.329	−1.163	2.089
ΔFertiliser	Change in use of fertiliser	0.267	0.525	−2.731	2.959
Gap_initial	Initial yield gap	1.104	0.597	−0.601	2.815
Comm	Dummy for highly commercialised or hybrid crops	0.331	0.471	0	1
ΔIPR_all	Change of IPR regime strength	0.229	0.449	−0.340	2.740
ΔIPR_plant	Change in IPR coverage for plant varieties	0.024	0.152	0	1
ΔUPOV	Change in UPOV membership status	0.029	0.168	0	1

leader country composite yield. When viewed over the time period in question, these yield differences are considerable, as shown in Table 2.

Table 3 provides descriptive statistics for the remaining variables. Data on harvested area are taken from FAO (2013) for the same time period as noted above. Data on agricultural mechanisation (tractors per 100 square kilometers of arable land), and fertilizer consumption (kilograms per hectare of arable land) are taken from World Bank (2012) and are provided only as national aggregations without reference to specific crops. IPR regime strength is drawn from two separate sources. The primary source is the Ginarte–Park Index (Ginarte & Park, 1997; Park, 2008; W. G. Park, personal communication, June 2012; Park & Wagh, 2002). This index covers the period 1960–2005 in five-year increments and scores countries' IPR regimes on a 0–5 scale, with five being the strongest regime. The index is used widely in the IPR literature (Campi & Nuvolari, 2013; Hudson & Minea, 2013; Kanwar & Evenson, 2003; Madsen & Timol, 2011) and is preferred to other measures, such as the Rapp–Rozek Index (Rapp & Rozek, 1990), because of its thoroughness.

The index includes 18 measures of regime strength. Eleven of these measures are directly or indirectly relevant to the topic of appropriability and agricultural technology: coverage for plant and animal varieties and for microorganisms; membership in the International Union for the Protection of New Varieties of Plants (UPOV); measures for recourse against imitators; and protection, enforcement, and duration. Taken as a whole, the IPR regime strength score represents a signal to innovators about the potential for appropriating rents from innovations transferred to and sold in a given developing country. However, since the aggregate index also covers IPR issues relevant to the manufacturing and service sectors, it is desirable to use a more refined IPR measure directly related to agriculture. To this end, we also introduce sub-indices from the Ginarte–Park Index directly related to agriculture: coverage for plant and animal varieties, and membership in UPOV. We also introduce a narrower measure of IPR regime strength with a simple dummy for the years in which country i was a member of UPOV from the International Union for the Protection of New Varieties of Plants (2012).

5. Results

Using the data described above, we estimate the model specified in Equation (1) with an Arellano–Bond linear dynamic panel-data estimation approach similar to that followed by Roodman (2006). We estimate the model with two sets of specifications. First, we estimate crop-specific models to compare yield gap convergence across crops. Second, we estimate the model by pooling all crops together to capture the overall effects of IPRs and other factors on yield gap convergence. Overall, our estimation results support the initial hypothesis that private sector incentives affect the flow of yield-enhancing agricultural technologies from industrialised to developing countries (Tables 4 and 5). However, several results are worth nothing.

5.1 Crop-Specific Estimations

Tables 4–6 show the crop-specific estimation results with different definitions of IPR regime strength and report results from diagnostic tests required to validate the model.[5] We observe several results that tentatively support the intuition underlying our model. First, our crop-specific estimation results indicate that all crops show decreasing yield gaps; that is, yield growth rate convergence over the past 50 years. The estimated diffusion parameters, β, are all less than one in absolute terms, although they vary in sign and significance levels. This suggests a decreasing yield gap across most crops. For example, the results for rice provide an estimate of β that is positive, less than 1, and significant under all definitions of IPR regime strength, which is consistent with the left-hand side of Figure 1. Results for barley and sorghum – where the estimate of β is negative and significant under several specifications – may suggest that countries farthest from the frontier are experiencing yield growth rates that exceed those of the leader country, but only for short periods of time, as in the right-hand side of Figure 1. Because these latter results suggest that our yield gap measures do not fully address short-term volatility in yields, we use the results as motivation for the pooled estimations discussed further below. The estimated coefficients α for cotton, millet, and soybeans are consistently negative and significant under all definitions of IPR regimes, which provides further evidence of convergence associated with a crop-specific 'backwards-advantage' or 'catching-up' effect.

Second, and at odds with Goeschl and Swanson (2000), our crop-specific estimates do not suggest that hybrid crops – namely, maize, and sorghum, as chosen in their study – exhibit significantly slower diffusion rates than other crops that may be attributable to the biological IPRs conferred by hybridisation. Specifically, our estimates indicate that the coefficient for maize – the most extensively hybridised crop in the world – is less than one and insignificantly different from zero, suggesting rapid yield gap convergence.

Third, we observe a weak correlation between legal IPRs and yield gap convergence captured by the coefficient θ. Table 4 shows the estimation results using the aggregate Ginarte–Park Index, indicating that an increase in IPR regime strength is associated with yield gap convergence for several of the selected crops. Because firms may respond slowly to a change in IPR regime strength in a given country, the effect is most significant for five- and 10-year lags, although sign and significance vary when moving from the Ginarte–Park Index (Table 4) to the plant variety protection subcomponent of the index (Table 5) and to UPOV membership (Table 6). In general, legal IPRs seem to be associated with yield gap convergence for rice and maize, although interpretation of coefficient values for the

Table 4. Arellano–Bond linear dynamic panel-data estimation with Ginarte–Park Index measures

Coefficient	Variable	Barley	Cotton	Maize	Millet	Rice	Sorghum	Soybean	Wheat
β	$G_{i,t-1}$	−0.173	−0.013	0.071	−0.155	0.121*	−0.129*	−0.047	−0.097
		(0.125)	(0.052)	(0.054)	(0.123)	(0.067)	(0.069)	(0.088)	(0.094)
γ_1	$\Delta Labor_{it}$	−0.162	0.019	−0.022	−0.141	0.101	0.123	−0.078	0.253**
		(0.303)	(0.198)	(0.103)	(0.147)	(0.167)	(0.159)	(0.101)	(0.124)
γ_2	$\Delta Area_{it}$	0.053	0.056**	0.023	−0.033	0.007	0.033	−0.070	−0.038
		(0.062)	(0.024)	(0.046)	(0.029)	(0.039)	(0.047)	(0.049)	(0.040)
γ_3	$\Delta Machinery_{it}$	−0.033	−0.053	−0.107***	−0.105**	−0.014	−0.040	−0.049	−0.005
		(0.048)	(0.057)	(0.040)	(0.047)	(0.020)	(0.040)	(0.047)	(0.057)
γ_4	$\Delta Fertilizer_{it}$	0.003	−0.047*	−0.047**	0.017	−0.013	0.014	0.046	−0.051*
		(0.045)	(0.028)	(0.019)	(0.031)	(0.022)	(0.023)	(0.040)	(0.029)
α	G_{i,t_0}	−0.040	−0.050***	−0.016	−0.041*	−0.019	0.003	−0.041**	−0.030
		(0.027)	(0.015)	(0.028)	(0.024)	(0.013)	(0.021)	(0.020)	(0.024)
θ_1	ΔIPR_{it}	0.038	−0.021	0.031	−0.043	−0.012	−0.015	−0.007	0.011
		(0.042)	(0.032)	(0.023)	(0.050)	(0.024)	(0.033)	(0.031)	(0.024)
θ_2	$\Delta IPR_{i,t-1}$	0.008	−0.044	−0.041**	−0.011	−0.051***	0.011	−0.021	0.002
		(0.040)	(0.031)	(0.020)	(0.076)	(0.017)	(0.057)	(0.023)	(0.027)
θ_3	$\Delta IPR_{i,t-2}$	0.026	0.031	0.031*	−0.029	−0.035*	−0.060	0.009	0.026
		(0.035)	(0.045)	(0.018)	(0.035)	(0.020)	(0.044)	(0.024)	(0.031)
AR(1) z stat (Pr > z)		−2.30 (0.02)	−3.94 (0.00)	−4.64 (0.00)	−2.35 (0.02)	−3.58 (0.00)	−3.50 (0.00)	−2.57 (0.01)	−2.69 (0.01)
AR(2) z stat (Pr > z)		0.95 (0.34)	0.40 (0.67)	0.16 (0.87)	−1.24 (0.22)	−0.68 (0.50)	1.20 (0.23)	0.50 (0.62)	0.07 (0.95)
Hansen J stat (Pr > χ^2)		17.90 (0.46)	20.58 (0.30)	15.89 (0.60)	21.84 (0.24)	21.72 (0.24)	19.39 (0.37)	11.05 (0.89)	18.76 (0.41)
Diff-in-Hansen J stat (Pr > χ^2)		16.80 (0.33)	18.13 (0.26)	12.96 (0.61)	18.47 (0.24)	19.91 (0.18)	17.96 (0.27)	8.43 (0.91)	17.81 (0.27)
Number of countries		30	53	74	38	68	51	28	42
Number of instruments		34	34	34	34	34	34	34	34
Number of observations		210	371	518	266	476	357	196	294

Notes: Robust standard errors are in parentheses. Coefficient estimates are significant at the *10 per cent, **5 per cent, and ***1 per cent levels, respectively. Coefficients for fixed year effects are omitted because of space limitations.

Table 5. Arellano–Bond linear dynamic panel-data estimation with Ginarte–Park Index subcategory measures

Coefficient	Variable	Barley	Cotton	Maize	Millet	Rice	Sorghum	Soybean	Wheat
β	$G_{i,t-1}$	−0.127	−0.012	0.055	−0.146	0.119*	−0.139**	0.030	−0.085
		(0.122)	(0.055)	(0.052)	(0.117)	(0.069)	(0.062)	(0.093)	(0.093)
γ_1	$\Delta Labor_{it}$	−0.290	0.000	0.001	−0.113	0.123	0.149	−0.074	0.289**
		(0.265)	(0.203)	(0.104)	(0.154)	(0.194)	(0.156)	(0.124)	(0.147)
γ_2	$\Delta Area_{it}$	0.088	0.056**	0.028	−0.022	0.018	0.038	−0.092*	−0.028
		(0.067)	(0.023)	(0.045)	(0.031)	(0.042)	(0.038)	(0.048)	(0.040)
γ_3	$\Delta Machinery_{it}$	−0.023	−0.066	−0.096**	−0.101**	−0.013	−0.047	−0.047	0.009
		(0.037)	(0.054)	(0.041)	(0.042)	(0.021)	(0.043)	(0.035)	(0.047)
γ_4	$\Delta Fertilizer_{it}$	−0.002	−0.045	−0.052***	0.012	−0.018	0.002	0.049	−0.057*
		(0.043)	(0.028)	(0.019)	(0.029)	(0.023)	(0.024)	(0.039)	(0.032)
α	G_{i,t_0}	−0.038	−0.045***	−0.014	−0.042*	−0.008	0.013	−0.035**	−0.023
		(0.028)	(0.015)	(0.027)	(0.024)	(0.012)	(0.021)	(0.015)	(0.025)
θ_1	$\Delta IPR\_Plant_{i,t}$	0.062	0.070	0.015	0.090	−0.029	0.142	0.017	0.078*
		(0.063)	(0.127)	(0.038)	(0.074)	(0.032)	(0.096)	(0.072)	(0.045)
θ_2	$\Delta IPR\_Plant_{i,t-1}$	−0.071	0.038	0.008	−0.031	0.009	−0.013	0.019	−0.005
		(0.049)	(0.078)	(0.040)	(0.080)	(0.030)	(0.044)	(0.039)	(0.034)
θ_3	$\Delta IPR\_Plant_{i,t-2}$	−0.083**	−0.016	0.088**	−0.046	0.013	0.084*	0.078	0.138
		(0.036)	(0.089)	(0.044)	(0.081)	(0.036)	(0.048)	(0.066)	(0.084)
AR(1) z stat (Pr > z)		−2.39 (0.02)	−3.80 (0.00)	−4.78 (0.00)	−2.42 (0.02)	−3.55 (0.00)	−3.64 (0.00)	−2.73 (0.01)	−2.63 (0.01)
AR(2) z stat (Pr > z)		1.06 (0.29)	0.37 (0.71)	0.04 (0.97)	−1.19 (0.23)	−0.63 (0.53)	1.17 (0.24)	0.82 (0.41)	0.10 (0.92)
Hansen J stat (Pr > χ^2)		18.52 (0.42)	21.18 (0.27)	15.20 (0.65)	21.12 (0.27)	25.12 (0.12)	17.32 (0.50)	10.55 (0.91)	19.26 (0.38)
Diff-in-Hansen J stat (Pr > χ^2)		16.72 (0.34)	15.00 (0.45)	12.61 (0.63)	17.87 (0.27)	22.34 (0.10)	16.73 (0.34)	7.16 (0.95)	15.03 (0.45)
Number of countries		30	53	74	38	68	51	28	42
Number of instruments		34	34	34	34	34	34	34	34
Number of observations		210	371	518	266	476	357	196	294

Notes: Robust standard errors given in parentheses. Coefficient estimates are significant at the *10 per cent, **5 per cent, and ***1 per cent levels, respectively. Coefficients for fixed year effects are omitted because of space limitations.

Table 6. Arellano–Bond linear dynamic panel-data estimation with UPOV membership

Coefficient	Variable	Barley	Cotton	Maize	Millet	Rice	Sorghum	Soybean	Wheat
β	$G_{i,t-1}$	−0.188*	−0.004	0.058	−0.138	0.114*	−0.146**	−0.017	−0.096
		(0.111)	(0.053)	(0.053)	(0.126)	(0.068)	(0.062)	(0.087)	(0.093)
γ_1	$\Delta Labor_{it}$	−0.265	−0.040	0.008	−0.113	0.161	0.149	−0.125	0.238*
		(0.240)	(0.189)	(0.109)	(0.162)	(0.192)	(0.153)	(0.103)	(0.124)
γ_2	$\Delta Area_{it}$	0.085	0.048**	0.027	−0.023	0.017	0.033	−0.063	−0.035
		(0.057)	(0.022)	(0.046)	(0.037)	(0.040)	(0.045)	(0.046)	(0.047)
γ_3	$\Delta Machinery_{it}$	−0.045	−0.068	−0.093**	−0.104**	−0.013	−0.048	−0.047	0.003
		(0.044)	(0.051)	(0.041)	(0.051)	(0.021)	(0.043)	(0.038)	(0.051)
γ_4	$\Delta Fertilizer_{it}$	0.024	−0.054*	−0.054***	0.016	−0.017	0.008	0.038	−0.055*
		(0.036)	(0.032)	(0.020)	(0.033)	(0.024)	(0.026)	(0.038)	(0.031)
α	G_{i,t_0}	−0.048**	−0.042***	−0.018	−0.049*	−0.007	0.009	−0.036**	−0.030
		(0.023)	(0.014)	(0.027)	(0.029)	(0.013)	(0.023)	(0.016)	(0.023)
θ_1	$\Delta UPOV_{i,t}$	−0.037	0.176	0.049	0.054	−0.029	0.011	−0.052	0.020
		(0.072)	(0.114)	(0.056)	(0.080)	(0.039)	(0.044)	(0.070)	(0.045)
θ_2	$\Delta UPOV_{i,t-1}$	−0.020	0.046	−0.023	−0.056	0.087**	−0.014	0.034	−0.015
		(0.039)	(0.059)	(0.036)	(0.128)	(0.040)	(0.060)	(0.058)	(0.042)
θ_3	$\Delta UPOV_{i,t-2}$	−0.242***	−0.043	0.026	0.025	0.101	0.171	0.078	−0.073
		(0.094)	(0.061)	(0.034)	(0.049)	(0.134)	(0.109)	(0.071)	(0.067)
AR(1) z stat (Pr > z)		−2.39 (0.02)	−3.83 (0.00)	−4.80 (0.00)	−2.35 (0.02)	−3.52 (0.00)	−3.59 (0.00)	−2.61 (0.01)	−2.69 (0.01)
AR(2) z stat (Pr > z)		1.00 (0.32)	0.45 (0.65)	0.11 (0.91)	−1.04 (0.30)	−0.71 (0.48)	1.16 (0.25)	0.58 (0.56)	0.07 (0.95)
Hansen J stat (Pr > χ^2)		12.15 (0.84)	19.72 (0.35)	15.15 (0.65)	22.49 (0.21)	24.68 (0.13)	19.96 (0.34)	10.05 (0.93)	19.24 (0.38)
Diff-in-Hansen J stat (Pr > χ^2)		8.67 (0.89)	17.93 (0.27)	12.90 (0.61)	18.47 (0.24)	22.11 (0.11)	19.77 (0.18)	6.28 (0.97)	14.34 (0.50)
Number of countries		30	53	74	38	68	51	28	42
Number of instruments		34	34	34	34	34	34	34	34
Number of observations		210	371	518	266	476	357	196	294

Notes: Robust standard errors given in parentheses. Coefficient estimates are significant at the *10 per cent, **5 per cent, and ***1 per cent levels, respectively. Coefficients for fixed year effects are omitted because of space limitations. UPOV = Union for the Protection of New Varieties of Plants.

Ginarte–Park Index is made difficult by the ordinal measurement of a composite indicator, such that increases in index values are not easily compared.

Fourth, we observe that our controls for growth in agricultural inputs are ambiguous or insignificant. Some coefficient estimates for labour are positive and significant, but most are not. Similarly, the estimated effects of harvested area are insignificant for most crops, suggesting that extensification and area expansion into more marginal land has little effect on yield gap convergence. Several coefficient estimates for machinery and fertiliser are negative and significant, for example in the cases of maize, cotton, millet, and wheat, suggesting that increases in use of these inputs is correlated with decreasing the yield gap for these crops. However, most of the input data in our study, for example agricultural labour, machinery, and fertiliser, are national aggregates rather than crop-specific measures, implying that the coefficient estimates may not capture crop-specific changes. We revisit this part of the estimation results in the pooled estimation below.

5.2 Pooled Estimations and Robustness Checks

Since our unit of measurement for these estimations – change in the yield growth rate – is comparable across all crops and key explanatory variables are not crop-specific, we can pool the data and estimate a set of similar models to generate additional results and test the robustness of our original specification. Results from the pooled estimation show coefficient estimates similar to the crop-specific estimations, indicating significant yield gap convergence, strong catching-up effect, and significant effects from legal IPRs, primarily in the five-year lags (Table 7, Models 1 and 2). We also find that the effects of agricultural input use on yield gap convergence are more clearly identified in the pooled estimation. The estimation results in Table 7 suggest that the increase in agricultural labour and the expansion of harvested area do not contribute to yield gap convergence. The intensification of agricultural mechanisation and fertiliser consumption, however, show significant effects in reducing the yield gap, which coincides with general findings in the literature.

The pooled estimation model allows us to explore several other hypotheses. First, to specifically test if crop reproductive biology (that is, hybridisation) affects yield gap convergence, we create a dummy variable that is interacted with the lagged yield gap variable to capture whether yield-enhancing technologies are embodied in hybrids versus open/self-pollinating varieties. Here, we chose maize and cotton but omitted sorghum. We chose maize because of the well-documented yield-enhancing effects of commercial hybrid seed sold in both developed and developing countries, cited earlier. We chose cotton because farmers typically purchase cotton seed – whether hybrid or not – rather than saving seed, because it is typically difficult or costly for farmers to extract seed from cotton lint for subsequent planting. We omitted sorghum because of the overwhelming absence of hybrid sorghum in sub-Saharan Africa. We also omitted soybeans, which, though highly commercialised in Latin America through the introduction of herbicide-tolerant genetically modified varieties, have been a factor for consideration only since 2000 at the earliest (Trigo, Cap, Malach, & Villarreal, 2010).

With the introduction of this interaction dummy, the estimation model becomes:

$$G_{it} = c_i + \beta_1 G_{i,t-1} + \beta_2 (Comm * G_{i,t-1}) + \alpha G_{i,t_0} + \sum_{j=1}^{4} \gamma_j \Delta X_{i,j} + \sum_{j=1}^{3} \theta_j \Delta IPR_{i,t-j-1} + \varepsilon_{it}, \qquad (4)$$

where *Comm* denotes the two crops that are more highly commercialised in terms of their reproductive biology. Estimates of β_2 are negative and significant under all three definitions of IPR regimes (Table 7, Models 3–5), suggesting more rapid yield gap convergence for hybrid crops such as maize and highly commercialised crops such as cotton, relative to other crops. Alternative definitions of this interaction dummy – including just maize and sorghum, as in the original Goeschl and Swanson (2000) model, or cotton, maize, and sorghum – yield similar results (see Online Appendix D). This

Table 7. Arellano–Bond linear dynamic panel-data estimation with pooled data

Coefficient	Variable	Model 1	Model 2: with interaction	Model 3: with interaction	Model 4: plant variety protection	Model 5: UPOV
β_1	$G_{i,t-1}$	−0.023	−0.024	0.152**	0.152**	0.147**
		(0.030)	(0.030)	(0.062)	(0.062)	(0.062)
β_2	Comm $*$ $G_{i,t-1}$			−0.439***	−0.440***	−0.436***
				(0.072)	(0.072)	(0.072)
γ_1	$\Delta Labor_{it}$		0.100*	0.106*	0.121**	0.110*
			(0.057)	(0.059)	(0.061)	(0.059)
γ_2	$\Delta Area_{it}$		−0.002	−0.012	−0.012	−0.012
			(0.017)	(0.017)	(0.017)	(0.017)
γ_3	$\Delta Machinery_{it}$		−0.055***	−0.058***	−0.056***	−0.056***
			(0.018)	(0.018)	(0.018)	(0.018)
γ_4	$\Delta Fertilizer_{it}$		−0.028**	−0.029**	−0.033***	−0.031**
			(0.011)	(0.012)	(0.012)	(0.012)
α	G_{i,t_0}	−0.024***	−0.026***	−0.028***	−0.025***	−0.026***
		(0.007)	(0.007)	(0.008)	(0.008)	(0.008)
θ_1	ΔIPR_{it}	0.002	0.004	0.005		
		(0.012)	(0.012)	(0.012)		
θ_2	$\Delta IPR_{i,t-1}$	−0.025**	−0.020*	−0.027**		
		(0.012)	(0.012)	(0.012)		
θ_3	$\Delta IPR_{i,t-2}$	0.006	0.011	0.007		
		(0.014)	(0.014)	(0.014)		
	$\Delta IPR\_Plant_{i,t}$				0.044*	
					(0.024)	
	$\Delta IPR\_Plant_{i,t-1}$				−0.024	
					(0.020)	
	$\Delta IPR\_Plant_{i,t-2}$				0.061**	
					(0.030)	
	$\Delta UPOV_{i,t}$					0.016
						(0.025)
	$\Delta UPOV_{i,t-1}$					0.019
						(0.023)
	$\Delta UPOV_{i,t-2}$					0.032
						(0.045)
AR(1) z statistics (Pr > z)		−9.75 (0.00)	−9.87 (0.00)	−9.19 (0.00)	−9.18 (0.00)	−9.19 (0.00)
AR(2) z statistics (Pr > z)		−0.96 (0.34)	−0.89 (0.38)	−0.12 (0.90)	−0.18 (0.86)	−0.20 (0.84)
Hansen J statistics (Pr > χ^2)		55.14 (0.01)	52.57 (0.02)	53.59 (0.01)	51.61 (0.02)	53.07 (0.02)
Difference-in-Hansen J statistics(Pr > χ^2)		36.68 (0.01)	42.44 (0.01)	43.62 (0.01)	38.06 (0.03)	39.96 (0.02)
Number of groups		384	384	384	384	384
Number of instruments		52	56	57	57	57
Number of observations		2688	2688	2688	2688	2688

Notes: Robust standard errors given in parentheses. Coefficient estimates are significant at the *10 per cent, **5 per cent, and ***1 per cent levels, respectively. Coefficients for fixed year effects and crop dummies are omitted because of space limitations. UPOV = Union for the Protection of New Varieties of Plants.

implies that hybridisation and commercialisation (in our narrow definition) may, in general, incentivise technology transfers that result in yield gap convergence between developed and developing countries.

Next, we explored whether alternative measures of IPR regime strength affect yield gap convergence. As with the crop-specific estimations we introduced the measure of patentability of plant varieties from the Ginarte–Park Index and membership status in UPOV. Results suggest that the patentability of plant varieties has an adverse effect on yield gap convergence: greater legal ability to patent plant varieties may widen the yield gap. Results also suggest that UPOV membership may have an insignificant effect on yield gap convergence (Table 7, Models 4 and 5, respectively). One interpretation of this result is that simply joining an international treaty or approving new IPR laws may not boost agricultural technology transfers as expected, particularly if not accompanied by enforcement of law and treaty. This result also suggests that a more comprehensive IPR regime measure, such as the Ginarte–Park Index, is more appropriate to the study of IPRs in developing countries.

Next, we explored the choice of countries used in our estimations and the definition of leader country. First, we returned to the crop-specific estimations to address the issue of whether variation in the countries used in each model might affect our results. We re-estimated our model using an identical set of 38 countries for cotton, maize, rice, and sorghum, noting that the remaining crops were not cultivated by a large enough set of countries to replicate this test further. Results (see Online Appendix E, Table 1) are generally consistent with our initial estimation results, suggesting that results are not driven by variation in countries chosen for each crop-specific estimation. Second, we re-estimated our pooled Model 3 with four alternative measures of leader country. These alternative measures fix the leader as the top country with the highest average yields across the entire period; fix the top three countries in the same manner; and choose the country with the highest yield in each year as the leader. Results (see Online Appendix F) suggest that alternative compositions do not affect our estimations results.

5.3 Discussion

Overall, results from our estimations are consistent with respect to yield gap convergence, consistent across varying definitions of legal and biological IPRs, and robust across models that use both crop-specific and pooled data. Alternative compositions of leader countries and controls for crop management practices yield similarly consistent results. Although these results are subject to several other interpretations, which we explore shortly, our findings support the argument that yield gap convergence between developed and developing countries during the period 1961–2010 is partly attributable to broad combinations of technological, institutional, and structural factors relating to both biological and legal IPRs. While legal IPRs play a role in yield gap convergence for some crops, the extent of the crop's commercialisation – or the need to purchase commercial seed rather than save seed from harvest – seems to be a strong driver. These findings further suggest that the combination of legal and biological IPRs may provide a strong set of innovation incentives for technology transfer in agriculture, as shown in the case of maize and cotton relative to the other crops examined above. This runs counter to arguments that temporary monopolies afforded by IPRs tend to limit technology transfers to developing countries, but does not apply to all crops investigated here.

Other explanations and interpretations are possible. First, it is clear that determinants of yield gap convergence are highly crop-specific. General conclusions about biological and legal IPRs cannot be drawn to the satisfaction of either opponents or proponents of stronger IPR regimes through legal or technological means. Second, one might interpret the contribution of IPR regime strength to yield gap convergence as a proxy for generalised improvement in the policy and investment climate for innovative firms rather than a specific incentive to plant breeders, seed companies, or other agriculture sector players.

Third – despite the extensive evidence suggesting that cultivar improvement has been a major contributor to yield gap convergence and productivity growth in developing-country agriculture – we recognise that yield growth is always an interaction between genetics and the environment, such that the absence of sufficiently high-resolution data on crop, soil, and water management limits any investigation of yield gap convergence. Although we attempt to address this with several alternative specifications of the model, it is unlikely that nationally aggregated data will be satisfying in this regard. Finally, a more complete treatment of the economic relationship between agricultural productivity growth and IPRs should include economic variables such as TFP growth rather than yield growth as its dependent variable, as well as more appropriate crop-specific time-series data on innovation incentives including, but not limited to, private sector technology transfers and spending on R&D.

Nonetheless, our findings should inform continued discussion on the appropriate role of IPRs in developing-country agriculture, especially given the renewed global interest in agricultural productivity growth that followed the 2007–2008 global food price crisis. If the past 50 years are any indication, future growth in developing-country crop yields will rely significantly on innovation incentives directed toward accelerating the rate of cultivar improvement. Future investment in cultivar improvement may increasingly emerge from the private sector, given the commercial viability of new technologies (including, but not limited to, biotechnology and genetic modification) and rising purchasing power among farmers and consumers in many developing countries. As such, future productivity growth will depend on the ability of developing-country policymakers to provide private innovators with the 'right' incentives to encourage productivity-enhancing investments in R&D.

6. Conclusion

Through a refinement of Goeschl and Swanson (2000), this paper examines the extent to which biological and legal IPRs encourage or constrain technology transfers from developed to developing countries. It does so with a model that decomposes yield gap convergence into four distinct components – technological, production, institutional, and structural – that affect the flow of yield-enhancing technologies from developed to developing countries. The model is estimated using data from the period 1961–2010 and an Arellano–Bond linear dynamic panel-data estimation approach.

Because the model focuses only on yield gaps, there are limits to what can be extracted with regard to wider issues of agricultural productivity growth in developing countries. Nonetheless, findings indicate that both biological and legal forms of IPRs promote yield gap convergence, with effects varying significantly between crops. Technological mechanisms, namely biological IPRs, seem to contribute to yield gap convergence resulting from crop reproductive biology for crops such as maize and cotton. Importantly, these findings refute Goeschl and Swanson (2000), who found that hybrid crops exhibit significantly slower yield gap convergence rates than other crops.

Legal IPRs, on the other hand, seem to contribute most significantly through the lagged effects of a broad strengthening of IPR regimes, rather than through IPRs that are specific to agriculture. This may suggest that changes in IPR regime strength are proxies for broader economic policy reforms such as trade liberalisation, public investment in science and innovation, or other indirect mechanisms. Alternative explanations or interpretations are possible.

Our results further suggest that combinations of biological and legal IPRs may incentivise technology transfers to developing countries, and that yield gap convergence attributable to these incentives may result from greater innovative activity in the private sector. However, the crop specificity of our findings also suggests that policies designed to strengthen IPRs related to agriculture may not be enough to stimulate broad-based private innovation and yield gap convergence. In sum, our conclusions about biological and legal IPRs are unlikely to satisfy either opponents or proponents of stronger IPR regimes, whether in academia, policymaking, or private enterprise. However, they do point to the potential importance of crop-specific analysis, policies, and investments.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Notes

1. Arguably, one issue in the application of an endogenous growth model to the study of yield gap convergence relates to the underlying assumptions of agent behaviour. Endogenous growth theory models assume that growth is a function of intertemporal decisions made by rational profit-maximising firms and utility-maximising consumers. While a yield growth model makes a similar assumption about developing-country firms that adapt technologies transferred from similar developed countries, consumers in this model are represented by farmers whose objective function may differ from analogous consumers in the endogenous growth model. That said, it is fair to assume that rational farmers in this yield growth model will adopt technologies that maximise profits, and that many such technologies inherently increase yields. As farmers choose yield-increasing technologies from a range of sources, including the global technology frontier, some convergence in yield growth rates between countries may result.
2. By extension, their study suggests that biological IPR mechanisms under development, for example genetic-use restriction technologies, advanced hybridisation systems, and other mechanisms based on crop reproductive biology designed to lower the cost of appropriating the gains from R&D, could impede future transfer of yield-enhancing technologies to developing countries (see also Goeschl & Swanson, 2003a, b).
3. Note that the growth rate of labour is closely correlated with country *i*'s population growth rate, which can also capture growth in the country's agricultural market size. Here, the underlying assumption is that a significant portion of the crop is used domestically for consumption or industrial purposes, therefore the change of the agricultural market size may affect the yield growth in a developing country. This is likely to be true with respect to the food staple crops and the countries estimated for this model. But because market size (measured in terms of agricultural GDP) and crop yields may be endogenously determined, the population growth rate and thus agricultural market size, can also be considered, following Galushko and Gray (2012). Here, the growth rate of the agricultural labour force provides a closely correlated measure of the overall population growth rate.
4. The choice of a log-linear functional form in this specification is consistent with both the original growth model posited by Barro and Sala-i-Martin (1995) and the model estimating yield gap convergence by Goeschl and Swanson (2000). Estimations using levels rather than logs do not affect the results in any significant manner and are available upon request from the authors.
5. Diagnostic tests are passed in the estimation for all crops, as follows. The Arellano–Bond autoregressive test for order 2 in all our model specifications does not reject the null hypothesis of no autocorrelation for at least a 5 per cent level of significance. The standard Hansen test and the difference-in-Hansen J tests for GMM estimation also show that our choice of instruments – that is, the further lags of yield gaps, as a group – are exogenous.

References

Acemoglu, D., Aghion, P., & Zilibotti, F. (2002). *Distance to frontier, selection and economic growth* (NBER Working Paper 9066). Retrieved from National Bureau of Economic Research, September 2013: http://www.nber.org/papers/w9066.pdf

Acemoglu, D., & Zilibotti, F. (2001). Productivity differences. *The Quarterly Journal of Economics*, *116*, 563–606. doi:10.1162/003355301511144104

Aghion, P., & Howitt, P. (2005). Growth with quality-improving innovations: An integrated framework. In P. Aghion & S. N. Durlauf (Eds.), *Handbook of economic growth* (Vol. 1A, pp. 67–110). Amsterdam: North Holland.

Aghion, P., Howitt, P., & Mayer-Foulkes, D. (2005). The effect of financial development on convergence: Theory and evidence. *Quarterly Journal of Economics*, *120*(1), 173–222.

Alston, J. M., Chan-Kang, C., Marra, M. C., Pardey, P. G., & Wyatt, T. J. (2000). *A meta-analysis of the rates of return to agricultural R&D: ex pede Herculem?* (IFPRI Research Report No. 113). Washington, DC: International Food Policy Research Institute.

Alston, J. M., Norton, G. W., & Pardey, P. G. (1995). *Science under scarcity.* Ithaca, NY: Cornell University Press.

Alston, J. M., Pardey, P. G., & Smith, V. H. (1999). *Paying for agricultural productivity.* Baltimore, MD: Johns Hopkins University Press.

Alston, J. M., & Venner, R. J. (2000). *The effects of the U.S. Plant Variety Protection Act on wheat genetic improvement* (EPTD Discussion Paper No. 62). Washington, DC: International Food Policy Research Institute.

Antle, J. M., & Capalbo, S. M. (1988). An introduction to recent developments in production theory and productivity measurement. In S. M. Capalbo & J. M. Antle (Eds.), *Agricultural productivity: Measurement and explanation* (pp. 17–95). Washington, DC: Resources for the Future.

Arellano, M., & Bond, S. (1991). Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *The Review of Economic Studies*, *58*(2), 277–297. doi:10.2307/2297968

Babcock, B. A., & Foster, W. E. (1991). Measuring the potential contribution of plant breeding to crop yields: Flue-cured tobacco, 1954–87. *American Journal of Agricultural Economics*, *73*, 850–859. doi:10.2307/1242837

Barro, R. J., & Sala-i-Martin, X. (1995). *Economic growth*. Cambridge, MA: MIT Press.

Basu, S., & Weil, D. N. (1998). Appropriate technology and growth. *The Quarterly Journal of Economics*, *113*, 1025–1054. doi:10.1162/003355398555829

Beddow, J. M., Pardey, P. G., & Alston, J. M. (2009). The shifting global patterns of agricultural productivity. *Choice*, *24*(4), 1–10.

Beintema, N., Stads, G., Fuglie, K., & Heisey, P. (2012). *ASTI Agricultural Science and Technology Indicators) global assessment of agricultural R&D spending*. Rome: ASTI.

Binenbaum, E., Nottenburg, C., Pardey, P. G., Wright, B. D., & Zambrano, P. (2003). South–north trade, intellectual property jurisdictions and freedom to operate in agricultural research on staple crops. *Economic Development and Cultural Change*, *51*(2), 309–335. doi:10.1086/edcc.2003.51.issue-2

Binswanger, H. P., & Von Braun, J. (1991). Technological change and commercialization in agriculture: The effect on the poor. *The World Bank Research Observer*, *6*(1), 57–80. doi:10.1093/wbro/6.1.57

Byerlee, D., Alex, G., & Echeverría, R. G. (2002). The evolution of public research systems in developing countries: Facing new challenges. In D. Byerlee & R. G. Echeverría (Eds.), *Agricultural research policy in an era of privatization* (pp. 19–34). Oxon: CABI.

Byerlee, D., & Fischer, K. (2002). Accessing modern science: Policy and institutional options for agricultural biotechnology in developing countries. *World Development*, *30*, 931–948. doi:10.1016/S0305-750X(02)00013-X

Campi, M., & Nuvolari, A. (2013). *Intellectual property protection in plant varieties. A new worldwide index (1961–2011)* (LEM Papers Series 2013/09). Pisa, Italy: Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced Studies.

Carew, R., & Devadoss, S. (2003). Quantifying the contribution of plant breeders' rights and transgenic varieties to canola yields: Evidence from Manitoba. *Canadian Journal of Agricultural Economics*, *51*, 371–395. doi:10.1111/j.1744-7976.2003.tb00181.x

Carew, R., Smith, E. G., & Grant, C. (2009). Factors influencing wheat yield and variability: Evidence from Manitoba, Canada. *Journal of Agricultural and Applied Economics*, *41*, 625–639.

Chin, J. C., & Grossman, G. M. (1990). Intellectual property rights and north-south trade. In R. W. Jones & A. O. Krueger (Eds.), *The political economy of international trade: Essays in honor of Robert E. Baldwin*. Cambridge: Basil Blackwell.

Coelli, T. J., Rao, D. S. P., & Battese, G. E. (1998). *An introduction to efficiency and productivity analysis*. Boston, MA: Kluwer Academic.

Deardorff, A. V. (1992). Welfare effects of global patent protection. *Economica*, *59*(233), 35–52. doi:10.2307/2555064

Eaton, D., Tripp, R., & Louwaars, N. (2006). *The effects of strengthened IPR regimes on the plant breeding sector in developing countries*. Paper presented at the International Association of Agricultural Economists 2006 Conference, Queensland, Australia.

Esposti, R. (2011). Convergence and divergence in regional agricultural productivity growth: Evidence from Italian regions, 1951–2002. *Agricultural Economics*, *42*(2), 153–169. doi:10.1111/j.1574-0862.2010.00508.x

Evenson, R. E., & Gollin, D. (Eds.). (2003). *Crop variety improvement and its effect on productivity: The impact of international agricultural research*. Wallingford, UK: CABI.

Evenson, R. E., & Kislev, Y. (1973). Research and productivity in wheat and maize. *Journal of Political Economy*, *81*(6), 1309–1329. doi:10.1086/jpe.1973.81.issue-6

Fan, S. (2000). Research investment and the economic returns to Chinese agricultural research. *Journal of Productivity Analysis*, *14*(2), 163–182. doi:10.1023/A:1007803108805

Fan, S., Hazell, P. B. R., & Thorat, S. (2000). Government spending, growth and poverty in rural India. *American Journal of Agricultural Economics*, *82*(4), 1038–1051. doi:10.1111/ajae.2000.82.issue-4

Fan, S., & Pardey, P. G. (1997). Research, productivity, and output growth in Chinese agriculture. *Journal of Development Economics*, *53*, 115–137. doi:10.1016/S0304-3878(97)00005-9

Feder, G., Just, R. E., & Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. *Economic Development and Cultural Change*, *33*(2), 255–298. doi:10.1086/edcc.1985.33.issue-2

Fischer, T., Byerlee, D., & Edmeades, G. O. (2014). *Global yields and global food security: Will yield increase continue to feed the world?* (ACIAR Monograph No. 158). Canberra: Australian Centre for International Agricultural Research.

Food and Agriculture Organization of the United Nations. (2013). FAOSTAT: Data on the production of crops. Retrieved from FAO, June–December 2013: http://faostat3.fao.org

Fuglie, K. O. (2012). Productivity growth and technology capital in the global agricultural economy. In K. O. Fuglie, V. E. Ball, & S. L. Wang (Eds.), *Productivity growth in agriculture: An international perspective*. Oxfordshire: CABI.

Fulginiti, L. E., Perrin, R. K., & Yu, B. (2004). Institutions and agricultural productivity in Sub-Saharan Africa. *Agricultural Economics*, *31*, 169–180. doi:10.1111/agec.2004.31.issue-2-3

Galushko, V., & Gray, R. (2012). *A re-examination of the role of intellectual property rights in U.S. seed exports*. Paper presented at the International Association of Agricultural Economists 2012 Conference, Foz Do Iguaçu, Brazil.

Gerpacio, R. V. (2003). The roles of public sector versus private sector in R&D and technology generation: The case of maize in Asia. *Agricultural Economics*, *29*, 319–330. doi:10.1111/j.1574-0862.2003.tb00168.x

Gerschenkron, A. (1962). Economic backwardness in historical perspective. In B. F. Hoselitz (Ed.), *The progress of underdeveloped areas*. Chicago: University of Chicago Press.

Ginarte, J. C., & Park, W. G. (1997). Determinants of patent rights: A cross-national study. *Research Policy*, *26*(3), 283–301. doi:10.1016/S0048-7333(97)00022-X

Gisselquist, D., & Jean-Marie, G. (2000). An argument for deregulating the transfer of agricultural technologies to developing countries. *The World Bank Economic Review*, *14*(1), 111–127. doi:10.1093/wber/14.1.111

Gisselquist, D., & Srivastava, J. (1997). *Easing barriers to movement of plant varieties for agricultural development* (World Bank Discussion Paper No. 367). Washington, DC: World Bank.

Goeschl, T., & Swanson, T. (2000). Genetic use-restriction technologies and the diffusion of yield gains to developing countries. *Journal of International Development*, *12*(8), 1159–1178. doi:10.1002/(ISSN)1099-1328

Goeschl, T., & Swanson, T. (2003a). The development impact of genetic use restriction technologies: A forecast based on the hybrid crop experience. *Environment and Development Economics*, *8*, 149–165. doi:10.1017/S1355770X03000081

Goeschl, T., & Swanson, T. (2003b). The diffusion of benefits from biotechnological developments: The impact of use restrictions on the distribution of benefits. In T. Swanson (Ed.), *The economics of managing biotechnologies*. New York, NY: Kluwer Academic.

Gruere, G., & Sun, Y. (2012). *Measuring the contribution of Bt cotton adoption to India's cotton yields leap* (IFPRI Discussion Paper No. 1170). Washington, DC: International Food Policy Research Institute.

Hayami, Y., & Ruttan, V. W. (1971). *Agricultural development: An international perspective*. Baltimore, MD: Johns Hopkins University Press.

Headey, D., Alauddin, M., & Rao, D. S. P. (2010). Explaining agricultural productivity growth: An international perspective. *Agricultural Economics*, *41*(1), 1–14. doi:10.1111/agec.2010.41.issue-1

Helpman, E. (1993). Innovation, imitation, and intellectual property rights. *Econometrica*, *61*(6), 1247–1280. doi:10.2307/2951642

Hudson, J., & Minea, A. (2013). Innovation, intellectual property rights, and economic development: A unified empirical investigation. *World Development*, *46*, 66–78. doi:10.1016/j.worlddev.2013.01.023

International Union for the Protection of New Varieties of Plants. (2012). *Members of the International Union for the Protection of New Varieties of Plants: UPOV Convention (1961),as revised at Geneva (1972, 1978 and 1991)*. Geneva: UPOV.

Johnston, B. F., & Mellor, J. W. (1961). The role of agriculture in economic development. *American Economic Review*, *41*(4), 566–593.

Kanwar, S., & Evenson, R. (2003). Does intellectual property protection spur technological change? *Oxford Economic Papers*, *55*(2), 235–264. doi:10.1093/oep/55.2.235

Kolady, D. E., & Lesser, W. (2009). But are they meritorious? Genetic productivity gains under plant intellectual property rights. *Journal of Agricultural Economics*, *60*, 62–79. doi:10.1111/j.1477-9552.2008.00171.x

Kolady, D. E., Spielman, D. J., & Cavalieri, A. (2012). The impact of seed policy reforms and intellectual property rights on crop productivity in India. *Journal of Agricultural Economics*, *63*(2), 361–384. doi:10.1111/j.1477-9552.2012.00335.x

Lai, E. (1998). International intellectual property rights protection and the rate of product innovation. *Journal of Development Economics*, *55*(1), 133–153. doi:10.1016/S0304-3878(97)00059-X

Lesser, W. (2000). An economic approach to identifying an 'Effective *sui generis* system' for plant variety protection under TRIPs. In V. Santaniello, R. Evenson, D. Zilberman, & G. Carlson (Eds.), *Agriculture and intellectual property rights*. Wallingford, UK: CABI.

Lesser, W., Horstkotte-Wesseler, G., Lele, U., & Byerlee, D. (2000). Intellectual property rights, agriculture, and the World Bank. In U. Lele, W. Lesser, & G. Horstkotte-Wesseler (Eds.), *Intellectual property rights in agriculture*. Washington, DC: World Bank.

Li, J., Xin, Y., & Yuan, L. (2010). Hybrid rice technology development: Ensuring China's food security. In D. J. Spielman & R. Pandya-Lorch (Eds.), *Proven successes in agricultural development: A technical compendium to millions fed*. Washington, DC: International Food Policy Research Institute.

Lipton, M., & Longhurst, R. (1989). *New seeds and poor people*. Baltimore, MD: Johns Hopkins University Press.

Madsen, J. B., & Timol, I. (2011). Long-run convergence in manufacturing and innovation-based models. *Review of Economics and Statistics*, *93*(4), 1155–1171. doi:10.1162/REST_a_00147

Mankiw, N. G., Romer, D., & Weil, D. N. (1992). A contribution to the empirics of economic growth. *The Quarterly Journal of Economics*, *107*, 407–437. doi:10.2307/2118477

McMullen, N. (1987). *Seeds and world agricultural progress* (NPA Report Series No. 227). Washington, DC: National Planning Association.

Naseem, A., Oehmke, J. F., & Schimmelpfennig, D. E. (2005). Does plant variety intellectual property protection improve farm productivity? Evidence from cotton varieties. *AgBioForum*, *8*, 100–107.

Naseem, A., Spielman, D. J., & Omamo, S. W. (2010). Private-sector investment in R&D: A review of policy options to promote its growth in developing-country agriculture. *Agribusiness*, *26*(1), 143–173. doi:10.1002/agr.20221

Nin, A., Arndt, C., Hertel, T. W., & Preckel, P. V. (2003). Bridging the gap between partial and total factor productivity measures using directional distance functions. *American Journal of Agricultural Economics*, *85*(4), 928–942. doi:10.1111/1467-8276.00498

Pardey, P. G., & Beintema, N. M. (2001). *Slow magic: Agricultural R&D a century after Mendel* (Technical Report 36). Washington, DC: International Food Policy Research Institute.

Parente, S. L., & Prescott, E. C. (1994). Barriers to technology adoption and development. *Journal of Political Economy*, *102*, 298–321. doi:10.1086/261933

Parente, S. L., & Prescott, E. C. (1999). Monopoly rights: A barrier to riches. *American Economic Review*, *89*, 1216–1233. doi:10.1257/aer.89.5.1216

Park, W. G. (2008). International patent protection: 1960–2005. *Research Policy*, *37*, 761–766. doi:10.1016/j.respol.2008.01.006

Park, W. G., & Wagh, S. (2002). Index of patent rights. In J. Gwartney & R. Lawson (Eds.), *Economic freedom of the world: 2002 annual report* (pp. 33–42). Vancouver: Fraser Institute.

Perrin, R. K., Kunnings, K., & Ihnen, L. A. (1983). *Some effects of the US Plant Variety Protection Act of 1970* (Economics Research Report 46). Raleigh, NC: North Carolina State University.

Pingali, P. L., & Traxler, G. (2002). Changing locus of agricultural research: Will the poor benefit from biotechnology and privatization trends? *Food Policy*, *27*(3), 223–238. doi:10.1016/S0306-9192(02)00012-X

Pray, C. E. (1992). Plant breeders' rights legislation, enforcement and R&D: Lessons for developing countries. In G. Peters & B. Stanton (Eds.), *Sustainable agricultural development: The role of international cooperation. Proceedings of the Twenty-First International Conference of Agricultural Economists*. Brookfield, VT: Dartmouth.

Pray, C. E., & Nagarajan, L. (2010). Pearl millet and sorghum improvement in India. In D. J. Spielman & R. Pandya-Lorch (Eds.), *Proven successes in agricultural development: A technical compendium to millions fed*. Washington, DC: International Food Policy Research Institute.

Ramaswami, B. (2002). Understanding the seed industry: Contemporary trends and analytical issues. *Indian Journal of Agricultural Economics*, *57*, 417–429.

Rapp, R., & Rozek, R. P. (1990). Benefits and costs of intellectual property protection in developing countries. *Journal of World Trade*, *25*(5), 76-–102.

Romer, P. M. (1994). The origins of endogenous growth. *Journal of Economic Perspectives*, *8*(1), 3–22. doi:10.1257/jep.8.1.3

Roodman, D. (2006). *How to do xtabond2: An introduction to "Difference" and "System" GMM in Stata* (Working Paper No.103). Washington, DC: Center for Global Development.

Schultz, T. W. (1968). *Economic growth and agriculture*. New York, NY: McGraw-Hill.

Smale, M., & Jayne, T. S. (2010). 'Seeds of success' in retrospect: Hybrid maize in Eastern and Southern Africa. In S. Haggblade & P. B. R. Hazell (Eds.), *Successes in African agriculture: Lessons for the future*. Baltimore, MD: Johns Hopkins University Press.

Spielman, D. J. (2007). Pro-poor agricultural biotechnology: Can the international research system deliver the goods? *Food Policy*, *32*, 189–204. doi:10.1016/j.foodpol.2006.05.002

Srinivasan, C., & Thirtle, C. (2000). Understanding the emergence of terminator technologies. *Journal of International Development*, *12*(8), 1147–1158. doi:10.1002/(ISSN)1099-1328

Sumberg, J. (2012). Mind the (yield) gap(s). *Food Security*, *4*(4), 509–518. doi:10.1007/s12571-012-0213-0

Taylor, M. S. (1993). TRIPs, trade and technology transfer. *The Canadian Journal of Economics*, *26*(3), 625–637. doi:10.2307/135891

Taylor, M. S. (1994). TRIPS, trade and growth. *International Economic Review*, *35*(2), 361–381. doi:10.2307/2527058

Trigo, E. J., Cap, E. J., Malach, V. N., & Villarreal, F. (2010). The case of zero-tillage technology in Argentina. In D. J. Spielman & R. Pandya-Lorch (Eds.), *Proven successes in agricultural development: A technical compendium to millions fed*. Washington, DC: International Food Policy Research Institute.

Trueblood, M. A., & Arnade, C. (2001). Crop yield convergence: How Russia's yield performance has compared to global yield leaders. *Comparative Economic Studies*, *43*(2), 59–81. doi:10.1057/ces.2001.8

Van Ittersum, M., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance—A review. *Field Crops Research*, *143*, 4–17. doi:10.1016/j.fcr.2012.09.009

Van Wart, J., Kersebaum, K. C., Peng, S., Milner, M., & Cassman, K. G. (2013). Estimating crop yield potential at regional to national scales. *Field Crops Research*, *143*, 34–43. doi:10.1016/j.fcr.2012.11.018

Wooldridge, J. M. (2010). *Econometric analysis of cross section and panel data* (2nd ed.). Cambridge, MA: MIT Press.

World Bank. (2012). *World development indicators*. Washington, DC: Author.