Intellectual Property Rights in Global Agriculture and their Impact on the Diffusion of Productivity Gains

Timo Goeschl and Timothy Swanson[1]

Introduction

Over the past 50 years, technological change within global agriculture has generated substantial increases in yields and productivity. Between 1950 and 1998, world per capita grain production increased by 15 per cent while global per capita harvested acreage declined by 50 per cent (Zilberman and Heiman, 1997). This occurred despite the pronounced increase in the world population over the same period. Table 1 gives a survey of yield developments in the eight most widely cultivated crops[2] — barley, cotton, maize, millet, rice, sorghum, soybeans and wheat — between 1961 and 1999. These are the major agricultural crops globally with global acreage of between 34 million hectares (cotton) and 214 million hectares (wheat); they are important crops in most parts of the developing and developed world[3].

Table 1. **Acreage, Global Distribution, Growth and Relative Yield Gap in Eight Major Crops**

Crop	Global acreage in million ha in 1999	Share of developing countries[a] in 1999 (%)	Share of developed countries[a] in 1999 (%)	Annual growth rate at the frontier, 1961–1999 (%)	Relative yield gap in 1999 (%)
Barley	58.6	28	72	1.53	-59.9
Cotton	34.3	72	28	2.45	-47.4
Maize	139.2	67	33	2.27	-72.4
Millet	37.2	96	4	0.93	-57.4
Rice	153.1	97	3	0.85	-57.9
Sorghum	44.8	90	10	2.08	-67.2
Soybeans	72.1	55	45	1.24	-40.0
Wheat	214.2	48	52	1.75	-54.5

a. The definition adopted in this table is based on the FAO definition. This differs slightly from the established definition used in the wider literature. The rest of this paper, adopts the customary definition Pardey *et al.* (1991).

Source: FAO; authors' calculations.

These global gains are very impressive in terms of aggregate yields and productivity, but they have not been distributed uniformly; many peoples benefit more or less than others from these changes in global agriculture. The uneven distribution of yield gains becomes evident in comparisons of current yields across large groups of countries — developed *versus* developing countries, for example. Table 1 reports the *relative yield gap* between developed and developing countries for each of these major crop varieties, i.e. the percentage by which developing countries lag behind the yield in developed countries in the specific crop. It shows that wide differences in global agricultural productivity persist. Across these crops, average yields in developing countries are about 57 per cent lower than the crop yields in developed countries[4]. Developing countries are therefore operating far off the productivity frontier in the agricultural sector and participating less in the general gains in global agriculture.

Why is technological change within agriculture benefiting some countries and not others? This might be expected on the grounds of differential capital endowments, infrastructure, climate or other factors that put producers in developing countries at a disadvantage[5]. The focus here, however, is on the persistence of such yield gaps in the presence of rapid technological change, i.e. on the phenomenon of diffusion. Why is it that yield gains resulting from technical change (admittedly occurring at the developed frontier) take significant amounts of time to diffuse to the developing countries within the frontier?

Any plausible explanation for this phenomenon must also explain another important and related characteristic: this relative yield gap differs significantly between crops. The gap for soybeans, for example, is around 40 per cent while for maize it is around 72 per cent. These are significant differences in experiences between crops, and they are the motivating evidence on which this paper rests. The authors believe that the primary factor explaining the variation in diffusion rates across crop varieties is the variation in property–rights structures affecting those crops. The object of the paper is to demonstrate how these structures have contributed to differential rates of diffusion of technical change, and hence to the uneven distribution of global yield gains. The aim is to review the evidence on differences in the patterns of diffusion of crop innovations, and in doing so to provide a case study of the contributions of various factors for the broader questions of innovation, property rights, diffusion and global welfare impacts. Situating the inquiry in the context of agriculture follows a tradition in the literature on the economics of technological change that originated with Griliches' seminal work on the diffusion of innovations (1957), Schmitz and Seckler on the social welfare impacts of mechanised production (1970), and Evenson *et al.* (1979) on the economic benefits from R&D.

The paper argues that differences in types of intellectual property rights protection can best explain these differences in relative yields across crops. This argument is based on the idea that the question of varying yield gaps is best analysed as a problem in the diffusion of innovations from an expanding productivity frontier to a set of receiver countries. Property–right regimes differ with respect to both the incentives for innovation and their impacts on the rate of diffusion. Strong regimes over innovations have two clear effects, advancing the rate of innovation at the frontier but also slowing the rate at which these innovations diffuse to countries off that frontier (Maskus, 2000). This implies a clear trade–off inherent within strong intellectual property right protection, which varies with the vantage point of the particular country concerned. The perceived benefits of strong protection depend on the country's initial positioning with respect to the technological frontier[6].

These questions are examined on the basis of a panel study of the yield development of eight crops across developing countries from 1961 to 1999[7]. These crops can be distinguished by the modes of property–right protection that innovations receive, with two enjoying technological ("strong") protection and six legal ("weak") protection[8]. The development of the crop yields across developing countries is examined for evidence on convergence and rates of diffusion; the likely explanations underlying this evidence are discussed and the evidence related to the respective property–rights regimes.

The analysis begins with a very simple model taken from Barro and Sala–i–Martin (1995) that captures concisely the link between innovation and diffusion and allows formulation of the equation estimated in the main part of the paper. It examines the empirical evidence on the convergence of crop yields in developing countries to developed–country levels over the observation period. This extension to the cross–sectional evidence presented in Table 1 is necessary in order to separate the spatial and inter–temporal factors that give rise to the pattern shown there. It then proceeds to estimate the rates of diffusion for each crop on the basis of the innovation–diffusion model of Barro and Sala–i–Martin. It also presents a decomposition of yield development in the average developing country into innovation, diffusion and structural components. These results are discussed and tested for robustness against other specifications. The final section argues that differences in the IPR regimes available for different crop varieties can best explain the measurable differences in the rate at which developing countries can benefit from innovations at the yield frontier. The paper concludes with a discussion of the implications of this result for optimal R&D policies in agriculture and the wider economy.

A Model of Innovation and Diffusion

A simple model of technological diffusion can be based on a theoretical framework commonly used in the context of growth and innovation. For the details of the model, see Barro and Sala–i–Martin (1995, Ch. 10). In this model, the source of technological progress lies in constant returns to scale to innovation in intermediate goods, in the spirit of Romer (1990). The particular multi–economy setting explored here is a leader–follower model in which there is a technological frontier at which innovations occur and are imitated by countries off the frontier. Countries have different endowments of inputs that allow them to produce final output and generate new products through innovation (leader) or imitation (follower). As Barro and Sala–i–Martin (1995) show, this setting allows a straightforward estimation of a convergence model.

Assume that a follower country's cost of imitation, v, is an increasing function of the ratio of the number of intermediate goods in the follower country (N_F) and the leader country (N_L), such that:

$$v = \psi\left(\frac{N_F}{N_L}\right) \tag{1}$$

with $\psi' > 0$ and $\psi'' < 0$. The usual conditions apply[9]. Barro and Sala–i–Martin then show that it is possible to derive the optimal ratio of goods in equilibrium, $R = N_F / N_L$, as a function of the factor endowments and the cost of imitation only. In other words, there is an R^* that is unique and optimal. If $N_F / N_L = R^*$, then the leader and the follower country are in a steady state characterised by a constant growth rate of N_F and N_L. If $N_F / N_L < R^*$, then $v < v^*$, i.e. imitation becomes cheaper as there is an abundance of useful products available to be copied. The result is a model with common convergence characteristics. An economy grows proportionately faster the farther it is below its steady state. Barro and Sala–i–Martin then formulate the result as a log–linear approximation such that:

$$\gamma_F = \gamma_L - \mu \cdot \log\left[\frac{R}{R^*}\right] \tag{2}$$

with γ denoting the growth rate of the follower and leader country, respectively, and μ denoting the speed of convergence. This can be transformed directly into:

$$\gamma_F = \gamma_L - \mu \cdot \log\left[\frac{{}^{y_F}\!/_{y_L}}{\left({}^{y_F}\!/_{y_L}\right)^*}\right] \tag{3}$$

This gives the growth rates for a country off the frontier (a follower) as the growth at the technological frontier (a leader country) minus the "friction" induced because imitations do not diffuse without cost, as μ is a positive transformation of the cost–of–imitation equation (1).

In the context of diffusion of innovations in crops, structural factors inhibit the diffusion of innovations and are likely to remain constant over time (Evenson and Kislev, 1973). The most important such factor involves agro–ecological barriers to diffusion that will limit the amount of innovations useful in a follower country. One way to interpret these barriers is to see them as equivalent to intrinsic productivity differences between the leader and follower countries in a particular crop. This can be accommodated within the given model as a statement that R^* is constant over time and specific to each follower country, implying a specific transmission ratio of innovations from the frontier to follower countries. With R^* constant, one can transform (3) to estimate the following model for each country:

$$\Delta G_{it} = a_i + \beta_i G_{i,t-1} + \varepsilon \tag{4}$$

with $G_{it} = \log\left(\frac{y_{i,t}}{y_t^*}\right)$ such that β is an estimator of the catch–up rate of the country i to the development at the frontier, denoted by a star (*), and $a_i < 0$ represents a measure of the country–specific structural barrier to an innovation from outside. Equation (4) states that differences in the growth path of crop yields can originate from two sources. First, inherent and persistent problems in the follower country impede it from keeping up with the yield dynamics in the leader country. These are captured in a country–specific estimation of a. Second, problems in the diffusion of innovations from the leader to the follower country are captured in the catch–up parameter β. Barro and Sala–i–Martin interpret the catch–up rate as a measure of the costs of imitation in the follower country. The higher β, the slower diffusion will occur.

Two fundamental assumptions underlie this model. One is that innovations take place only in those countries that make up the frontier. This paper claims that even though total expenditures on agricultural R&D in the developing countries combined are roughly the same as those in developed countries combined (Alston *et al.*, 1998)[10], technological factors result in the developed countries' R&D production function being significantly more efficient than that of developing countries. In sum, the vast majority of yield–enhancing innovations have been generated in the developed countries. One must concede, however, that in some crops, such as millet, the picture may be less clear cut. The second fundamental assumption is that country–specific factors are not allowed to influence the coefficient that estimates the rate of diffusion.

A couple of practical difficulties arise in the estimation. The most obvious is the meaningful definition of a frontier. Choosing a single country makes it difficult to distinguish between genuine technological progress and short term fluctuations in output. Second, interest centres on the differences in diffusion parameters between different crops, not the differences in diffusion between different countries. The question of the definition of the frontier will be settled in the next section and a first, indicative set of results on absolute convergence will be presented. The meaningful pooling of the data will then be addressed.

Growth in Crop Yields: Absolute Convergence to the Frontier

The first piece of empirical evidence is the yield frontier[11], reported in the third column of Table 1. For some degree of comparability between crops and years, the frontier is defined uniformly as the average yield in developed countries[12]. The yields at the productivity frontier in all of these crops rose steadily over 1961–99. The accumulated gains at the frontier varied considerably between crops, however. Rice had the smallest gains, an average of 0.9 per cent per year[13], while the improvements in cotton cultivation resulted in an average annual growth rate of 2.5 per cent. Other crops with comparable gains have been maize, sorghum and wheat, the yields of which more than or almost doubled.

The second piece of evidence concerns the success of developing countries in catching up to the frontier that has been expanding at different rates for different crops. A general claim within growth theory is that we would expect countries with lower productivity to experience more rapid productivity growth than the countries at the frontier. This process is known as “convergence”. Table 2 reports the results from a study of productivity growth rates in developing countries that regresses the average growth rate in country yields on the country’s initial productivity value across all countries for each crop. Figure 1 gives graphical representations of the procedure for maize, sorghum, wheat and rice. This exercise estimates a model of the standard form:

$$AVG = c + \beta \, log\left(Y_{1961}\right) + \varepsilon \qquad (5)$$

where AVG is the average growth rate over the observation period and Y_{1961} is the yield level in 1961. For most crops, the hypothesis that productivities converge over time is not rejected by the values of the coefficients: There is a negative relationship between initial yield levels and a country’s average growth rate over the following 38 years. This relationship is particularly strong in cotton, rice and wheat, somewhat less so in millet, soybeans and barley. What is striking is that for two crops, namely sorghum and maize, absolute convergence is rejected by the data.

These results imply little evidence that developing countries have experienced any catching–up in the yields of maize and sorghum. They are somewhat counter–intuitive. In these two crops, yield growth at the frontier has been at the higher end of the distribution, as Table 1 shows, which would be conducive to a catching–up process in developing countries. Support for this intuition comes from a significantly positive correlation between the growth rate at the frontier and the convergence coefficient β for all other crops except maize and sorghum. The correlation coefficient between the growth rate at the frontier and β is –0.01 based on the estimates of all eight crops. When omitting maize and sorghum, it jumps to 0.67, suggesting a significantly positive correlation.

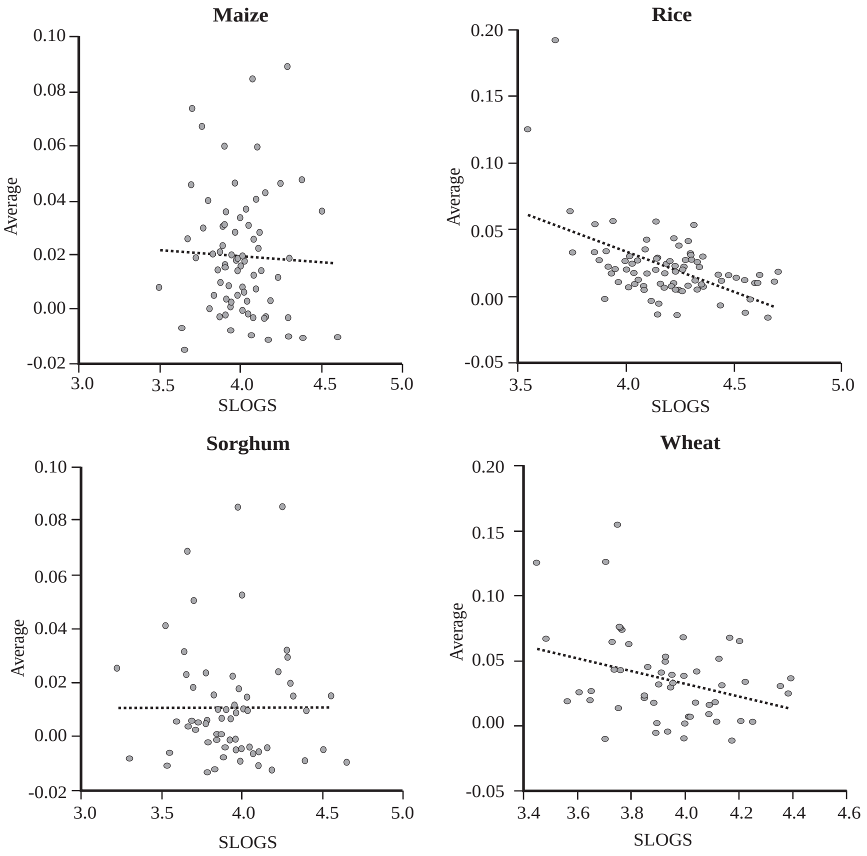
The empirical account of yield growth at the frontier and of the catching–up process of those countries that lag behind the frontier has two major implications. First, there is evidence that differences in the yield gaps between crops presented in Table 1 reflect more than a historical carry–over from some initial distribution of gaps. Otherwise, the evidence on convergence would not correlate so closely with growth at the frontier for most crops. Differences in the rate of expansion do matter. After all, one explanation could have been that the reason for the current gaps can be found in the same gaps being present 40 years ago, thus pointing to some factor that remained invariant across this period[14]. Second, the account raises questions about the presence of unconditional convergence in yields in developing countries. The data for maize and sorghum (see Figure 1) indicate that crucial determinants of the rate of convergence

Table 2. **Regressions for Convergence of Crop Yields, 1961-99**

	Barley	Cotton	Maize	Millet	Rice	Sorghum	Soy	Wheat
β	-0.0409	-0.0930	-0.0046	-0.0417	-0.0607	-0.0002	-0.0383	-0.0501
	(0.0143)**	(0.0150)**	(0.0134)	(0.0124)**	(0.0114)**	(0.0105)	(0.0112)**	(0.0204)*
R^2	0.180	0.399	0.016	0.203	0.265	0.000	0.280	0.104
(No. of obs.)	(39)	(60)	(75)	(46)	(80)	(63)	(32)	(54)

Notes: Standard errors in parentheses; * refers to significance at 5 per cent level, ** to significance at 1 per cent level.

Figure 1. **Growth versus Initial Yields in Four Crops**



Note: SLOGS = log (Yield initial year). Average = avg. yield growth rate.

exist *other than* the yield gap that ensures that developing countries can benefit from a technological gradient. The remainder of this paper aims to provide an answer to this puzzle of conditional convergence in crops. Its main proposition is that the solution lies in rates of diffusion of yield gains to developing countries that differ significantly between crops.

The Diffusion of Innovations

This section estimates the rates of diffusion of innovations for different crops in order to resolve the puzzle of the relative gaps and of conditional convergence. The crop specificity of technological protection enables comparing the performance of each of these regimes with respect to diffusion. A particular feature of this analysis is its decomposition of the development of the yield gap in each crop into its three basic components: *1)* innovations at the frontier, *2)* the diffusion process of these innovations to developing countries, and *3)* the country–specific factors that impact on the capacity for yield growth, such as specific agro–ecological conditions. The first will tend to increase yields as the set of technological possibilities expands. The second will decelerate the speed at which these gains reach developing countries, and the third will determine the long–run capacity of a country to experience yield growth in a particular crop at a rate above or below the growth rate at the frontier.

Estimating the Econometric Model

To assess the diffusion patterns in each crop, one can study the development of agricultural yields in developing and developed countries for the eight crops chosen, based on FAO data covering 39 years, from 1961 to 1999. The amounts of data available for each crop differ due to varying cultivation areas and completeness of data over the entire estimation period. For soybeans, there are 38 observations available from 27 countries, while for maize there are 38 observations from 82 countries[15].

The method used is a fixed–effect panel estimation model that allows for heterogeneity among the countries through variable intercepts (Hsiao, 1986). To estimate the Barro–Sala–i–Martin diffusion model consistently, one must convert it into a form that presumes that all developing countries are subject to the same exogenous stochastic shock, in this case an innovation that sets countries back in their relative yields. It then estimates for each crop the rate at which this shock is compensated for, allowing for heterogeneity in the intrinsic "rate of recovery" between countries. The model has the form:

$$\Delta G_{it} = a_i + \beta G_{i,t-1} + \varepsilon \tag{6}$$

where *G* is the gap in growth rates between the specific country and the lead country, Δ signifies the change in the gap and ε is a normally distributed random variable with $E(\varepsilon)=0$ and a known variance. The intercept term *a* denotes the long–term difference in productivity growth in equilibrium, regarded as a country–specific intercept that captures the agro–ecological and institutional factors that influence the overall productivity development of the country. In this it captures the content of the hypotheses that claim country–specific factors as responsible for the disproportionate yield gap for maize and sorghum. The coefficient β to be estimated then reports the diffusion coefficient of the particular crop.

Empirically, the growth rates of the frontier and the country *i* enter in the form of $log\ (y_{it})$ with *y* denoting the yield of country *i*. The diffusion coefficient β is then estimated as a GLS–regression, correcting for cross–section heteroskedasticity in the residuals by down–weighting each pool equation with an estimate of the cross–section residual standard deviation[16].

Econometric Results

Table 3 reports the results for the different crops. Each of the estimations delivers a coefficient β that is statistically highly significant. Also reported is a parameter $\tilde{a}$ that denotes the *average* intercept for all countries in the estimation. Since the model is restricted to a common slope coefficient, a high number of observations can be expected to result in a low R–squared. The Durbin–Watson coefficients indicate that serial correlation is not a particular problem for this estimation, thus strengthening a claim that the results provide an analysis independent from the trends at the frontier.

Table 3. **Regressions for Diffusion of Innovations in Different Crops**

	Barley	Cotton	Maize	Millet	Rice	Sorghum	Soy	Wheat
β	-0.326	-0.318	-0.249	-0.335	-0.254	-0.283	-0.469	-0.387
	(0.0203)**	(0.0150)**	(0.0117)**	(0.0184)**	(0.0142)**	(0.0138)**	(0.0271)**	(0.0184)**
$\hat{a}$	-0.339	-0.294	-0.365	-0.294	-0.230	-0.369	-0.291	-0.384
R^2	0.171	0.166	0.135	0.172	0.154	0.160	0.244	0.234
(No. of obs.)	(35)	(54)	(82)	(44)	(71)	(62)	(27)	(48)
DW-Statistic	2.40	2.26	2.40	2.45	2.23	2.42	2.27	2.30

Notes: Figures in first set of parentheses are standard errors; ** refers to significant at the 1 per cent. level.

Before interpreting the results, some convenient algebra can bring the model into a simpler form. Re–arranging (2) produces the following equation for the growth rate of yield, $\Delta\hat{y}_t$, in the average developing country:

$$\Delta\hat{y}_t = \Delta y_t^*\left(1+\beta\right)G_{t,t-1} + \hat{a} + \varepsilon \qquad (7)$$

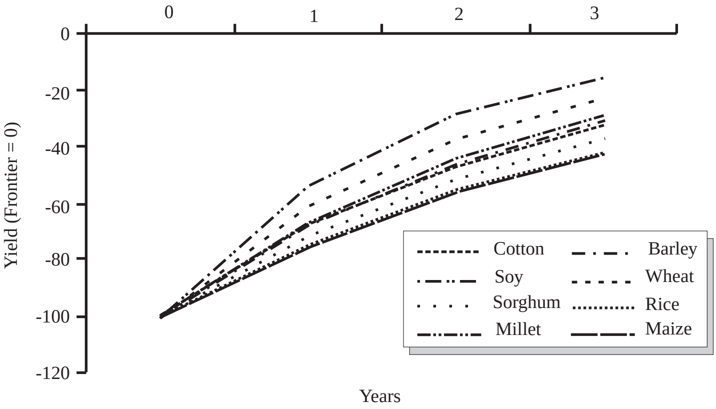
This formulation reveals the separate components that drive the growth rates of yields. The first is the yield gain at the frontier Δy^*. It reflects the expansion of the set of technological possibilities. The second captures the extent to which an innovation can diffuse in the country, with the gap G defined to take on positive values. The expected sign on β thus is negative (indicating that innovations do not have a negative effect on growth) and the closer the coefficient is to –1, the more rapid the gains dissipate from the frontier to the average developing country. The third parameter, $\hat{a}$, summarises the country–specific growth lags as an average. A positive value would indicate that, on average, developing countries have a higher "intrinsic" rate of yield growth in the crop.

Interpreting the Results: Diffusion

The results indicate considerable differences among the diffusion coefficients in the crops under examination. The crops fall roughly into three groups. Rapid diffusion happened only for soybeans with a diffusion coefficient well below –0.45 (in absolute terms). Moderate diffusion (below –0.3) occurred in wheat, millet, barley, and cotton. In sorghum, rice, and maize, diffusion has been slow (above –0.3), such that gains from innovation have taken a relatively long time to reach developing countries.

To give a more concrete impression of the differences in the rates of diffusion, Figure 2 displays the results of a simulated diffusion situation. It shows the process of catching up in different crops after an innovation at the frontier in the initial period that sets back all crops by the same amount. The graph demonstrates how differently diffusion occurs in these crops.

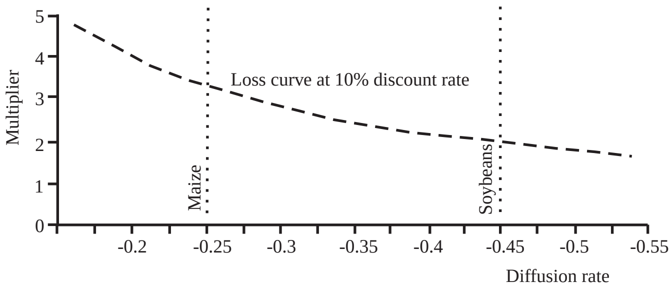
Figure 2. **Catching up under Different Rates of Diffusion**



After two periods, the "best"–diffusing crop has made up 72 per cent of the initial shock while the "worst"–diffusing crop has compensated for only 43 per cent. The absolute difference carries on for another year before the slower–diffusing crops start to close the gap. Yet even after nine periods, when the yield in the "best" crop, soybeans, has converged to more than 99 per cent of the frontier yield, the "worst" crop, maize, still lags by more than ten per cent. Eventually, of course, all crops catch up.

For individuals cultivating different crops, an important criterion for evaluating them is the loss of yield suffered as a result of slow diffusion. This throws a different light on the problem, as it looks at the impacts of the cumulative process of diffusion. Figure 3 reports the multiplier to the initial shock, to estimate the net present value of the loss at a ten per cent discount rate[17]. The graph shows that the differences between the rates of diffusion in maize and soybeans cause a farmer to suffer roughly double the economic loss in maize compared with soybeans when an innovation at the frontier shifts the farm away from the frontier.

Figure 3. **Loss Multiplier as a Function of the Diffusion Rate**



Other Effects: Country–Specific Lags

A second set of important differences arises from the country–specific data on "individual growth capacity". It reveals first that, on average, developing countries would experience slower growth in all crop yields, because the coefficient ($\hat{a}$) is below zero for all crops. These impediments to growth differ between crops, however, ranging from rice, with good intrinsic growth potential at $\hat{a} = -0.230$, to wheat, with high average barriers to growth at $\hat{a} = -0.384$. This captures the history–dependent nature of diffusion for each crop. The level of the coefficient indicates whether the pattern of diffusion encounters local conditions either more beneficial or more adverse to successful cultivation of the plant[18]. There is no correlation between parameter estimates of $\hat{a}$ and β, which indicates that the processes of diffusion are disjoint from the effects of local conditions[19]. Another informative statistic shows how diverse countries are in their experience. In sorghum, cotton and soy, there is a wide dispersion of local coefficients, indicated by the variance–to–mean ratio $r=s_i^2/m_i>5$, while they are fairly similar between countries for the other crops, where $r<4$.

In general, the other factors explored generate little more explanatory value[20]. It seems that the rate of innovation at the technological frontier and the rate of diffusion of innovation within the frontier explain the vast majority of the patterns of yield growth across the developing world. Annex A contains diagrams demonstrating the actual and fitted patterns of yield development across developing countries, showing the manner in which this development tracked that at the frontier for the various crop varieties.

Testing for the Role of Property Rights in Diffusion

This paper has put forward three sets of observations on crop–yield developments across developing countries. The first set out the average yield gaps between developed and developing countries. They are large across the entire range of crops (between 40 per cent and 60 per cent) but the two outliers in the group clearly are maize (72 per cent) and sorghum (67 per cent). The second consisted of a test for "absolute convergence" across all varieties — whether countries with lower yields at the beginning of the period (1961) experienced higher average growth rates over the ensuing years to 1999. This exercise showed that only sorghum and maize do not exhibit absolute convergence, indicating the presence of convergence–limiting factors for these two species. The third examined the rates of diffusion from the technological frontier to developing countries. It revealed significant differences in the rates of diffusion of innovation between crops, with diffusion particularly slow in maize, sorghum. Based on a standard innovation–diffusion model (Barro and Sala–i–Martin, 1995), this can be interpreted as evidence for higher imitation costs in these two crops. In each part of the study, maize and sorghum emerged as the distinctive crops in the relationship between developed and developing country crop yields. What can one hypothesise concerning the reasons underlying these observations of these crops' relative performances?

In the diffusion model used here, differences in the diffusion coefficients indicate differences in the cost of imitation, i.e. the cost of transferring an innovation from its developed–country origin to a developing–country context. An important determinant of that cost for crops is how readily the value–adding traits in a novel variety from the leader country can be identified and extracted by the follower. This in turn is significantly influenced by the form of property–right protection afforded to the value–adding traits within the innovative variety.

There is no question that property rights may be claimed in innovative plant varieties[21], but the capacity to protect these claims varies. At present there are two principal forms of protection: *1)* "Legal protection", which is dependent for effect on the resources expended on monitoring and enforcement by the follower country; and

2) “Technological protection”, which is independent of the resources expended by the follower for effectiveness. It is probably fair to assert that over the past 40 years little legal protection has been afforded to intellectual property–rights claims to innovations in plant varieties throughout most of the developing world. Since most developing countries have had little to gain from expending resources on the implementation or enforcement of property rights for the benefit of innovators situated primarily overseas, there have been minimal incentives for such expenditures[22]. Therefore, it is likely that the primary route available for the effective protection of intellectual property right claims in developing countries has been technological.

Currently, technological protection is available only in the form of modern hybrid varieties, and thus limited in practice to the “outbreeding crops”, maize and sorghum. Hybridisation affords protection to improved varieties of these species, because the seed from them sold to farmers represents a relatively diverse gene pool and subsequent re–plantings generate widely divergent varieties. The other crop species reproduce asexually, making parents and offspring identical in genetic structure. Sales of improved varieties from these species may be copied perfectly (and almost costlessly) from purchased seed, unless national laws effectively prevent such practices.

For these reasons, one can claim that the technologically protected species act in effect as a case study on the impact of effective or “strong” property rights in innovation. They may be contrasted with the impacts of innovations in the non–technologically protected species that act, in developing countries, as “weakly” protected innovations. Maize and sorghum have the unique capacity for technological protection of innovations; they represent the lines down which strong property rights protection has been in effect over the past fifty years[23].

Modelling Diffusion under Varying Property Right Regimes

One may test for the presence of a differential in the rate of diffusion through a dummy variable for observations involving a hybrid crop. The model then estimates for each category the rate at which the shock (innovation) is compensated, allowing for heterogeneity in the intrinsic “rate of recovery” between countries. The model has the form:

$$\Delta G_{it} = a_i + \beta G_{i,t-1} + \gamma D G_{i,t-1} + \varepsilon \qquad (8)$$

where G is the gap (difference) in logarithm between the yields in a specific country and the lead country and Δ signifies the change in the gap. The intercept term a_i denotes the long–term difference in productivity growth in equilibrium. As noted above, one way of interpreting a_i is to regard it as a country–specific intercept that captures the agro–ecological and institutional factors that influence the overall productivity development of the country. In this it captures the content of the hypotheses that claim country–specific factors as responsible for the disproportionate yield gap that exists for maize and sorghum. The estimated coefficient β then reports the diffusion coefficient across all crops and γ is the diffusion rate differential for hybrids crops identified through the dummy variable D[24]. Empirically, Fisher's test as proposed by Maddala and Wu (1999) serves as a panel data unit root test. The diffusion coefficient β and the diffusion rate differential γ are estimated according to equation (9) as a GLS–regression, correcting for cross–section heteroskedasticity in the residuals by down–weighting each pool equation with an estimate of the cross–section residual standard deviation[25].

Econometric results

The estimation delivers coefficients β and γ that are statistically highly significant. It also delivers, as in the previous exercise, the average intercept for all countries in the estimation denoted by $\hat{a}$. Before interpreting the results, it is once again convenient to perform some algebra to convert the model into a simpler form. Re–arranging (8), the following equation emerges for the growth rate of yield, $\Delta\hat{y}_t$, in the average developing country:

$$\Delta\hat{y}_t = \Delta y_t^* - \left(1 + \beta + \gamma D\right) G_{t,t-1} + \hat{a} + \varepsilon \qquad (9)$$

This formulation highlights the separate components that drive the growth rate of yields. The first component is the yield gain at the frontier Δy^*. It reflects the expansion of the set of technological possibilities. The second component captures the extent to which an innovation can diffuse in the country, with the gap G defined to take on positive values. Therefore, one would expect that the coefficient β is negative (indicating that innovations do not have a negative effect on growth) and that the closer the coefficient is to –1, the more rapid the gains dissipate from the frontier to the average developing country. The third component, γD is the effect of hybridisation on the growth rate. The fourth parameter, $\hat{a}$, summarises the country–specific growth lags as an average. A positive value would indicate that on average, developing countries have a higher "intrinsic" rate of yield growth in this crop and vice versa.

Table 4 shows the results of the econometric estimation. The most important result is that hybridisation has a measurable impact on the rate of diffusion. The coefficient of the hybrid dummy variable is highly significant, despite allowing for fixed effects both by country and by crop. The rate of diffusion of innovations from the frontier to developing countries across all crops was such that crops carried over roughly 69 per cent of the gap opened by an innovation into the next year. The "diffusion penalty" involved in having innovations occur predominantly in hybridised crops is about 7.1 per cent per year. This means that developing countries retained about seven per cent more of the yield gap each year in hybrids than in non–hybrids. It explains an important part of the cumulative yield gap that has developed in hybrids. The results also indicate merit in the idea that structural effects, such as agro–ecological conditions, have contributed to inhibiting yield growth of hybrids in developing countries. The parameter $\hat{a}$ is the mean of the individually estimated parameters a_i. The means computed for hybrids and non–hybrids indicate that in hybrids

Table 4. **Regressions for Diffusion of Innovations in Different Crops**

β	γ	$\hat{a}$	R^2	DW-statistic
-0.313	0.071	-0.33611	0.16	2.39
(0.008)**	(0.011)**		No. of obs.: 14 858	

Note: Standard errors are in parentheses. ** refers to significance at the 1 per cent level.

the average developing country has had a greater negative long–term deviation from the growth rate of the frontier than in non–hybrids. The combination of structural and diffusion effects is therefore responsible for the significant gap in yields that persists between developed and developing countries in hybrid crops.

The authors believe that the observed differences in yield growth and diffusion across crop varieties are attributable to the distinctive property–right regimes available for claiming rights to innovation in these varieties. The observations are consistent with the idea that strong property–right regimes have resulted in varying costs of imitation across countries, which increase with the distance of the country from the technological frontier. This increasing cost of imitation translates into the observed consequence that innovations are impacted and slow to diffuse, especially for the two crops afforded effective protection. The ultimate outcome is that the two crops in which strong property rights exist are the only two which do not exhibit absolute convergence. The poorer countries fail to "catch up", only for those crops where strong intellectual property rights regimes prevail. Finally, this failure to catch up is captured in aggregate terms in the relative lags between the yields in developing and developed countries. All of the observations on crop yields and changes across the past forty years are consistent with the hypothesis that strong property–rights protection over innovations inhibits their diffusion across the developing world.

If this is the case, it provides significant evidence in the general debate about the global impact of enhanced property–right regimes. These observations imply that the receipt of benefits from strong property–rights protection is inversely related to the distance of the particular country from the technological frontier. Thus, even if innovation occurs more rapidly under strong protection, countries far from the frontier might prefer the combined rate of innovation/diffusion inherent within a weaker form of regime. All intellectual property rights regimes would entail an inherent trade–off between innovation and diffusion, and the preferred regime would depend upon the perspective (i.e. technological level) of the country concerned (Krugman, 1979; Lai, 1999).

Conclusion

This paper has examined the development of yields in developing and developed countries in the eight most important agricultural crops over a period of almost forty years. The results indicate that although yield growth has been impressive, problems in global distribution of agricultural productivity persist and give cause for concern. They also indicate significant differences that require explanation in both the dynamics of yield growth in the developed countries and the diffusion between crops of these gains to developing countries. Evidence on the convergence of yields in developing countries shows that it occurs in all crops examined with the exception of maize and sorghum. Exploring the reasons for this difference by estimating the diffusion coefficients of innovations from the yield frontier to developing countries leads to a conclusion that the failure of convergence in maize and sorghum can be explained by the exceptionally low rate of diffusion in these two crops. At the same time, agro–ecological factors are likely to affect diffusion, but cannot explain the exceptional cases of maize and sorghum.

Maize and sorghum are exceptional because hybrid seeds have been available for them alone over the past fifty years. This has led to higher than average yield growth through the mobilisation of private R&D efforts. At the same time, the results here indicate that the technological protection of property–rights claims afforded by hybridisation has had a negative effect on the rate of diffusion of these innovations. The existence of this innovation–diffusion trade–off highlights the problematic international welfare implications inherent in choosing a particular intellectual property protection regime. This empirical study quantifies the trade–off exactly for the main crop varieties and decomposes yield growth in the average developing country as a combination of innovation at the frontier, diffusion to the developing country and structural factors in the adoption of new varieties.

Crop varieties provide a possibly unique setting within which the debate over the impacts of enhanced property–right regimes might be tested. The initial evidence here indicates an inherent trade–off between enhanced rates of innovation (and thus growth) and enhanced rates of diffusion (and hence distribution). This means that there are frictions within the system of technological dissemination that inhibit the flows of beneficial information, and that enhanced property–rights regimes will work most prominently against the interests of those states farthest from the frontier. Although the results are preliminary, they give cause for concern about the promotion of property–rights regimes with such profound distributional implications.

Notes

1. This research has its origins in a research grant from the UK Department for International Development. We are grateful to Robert Carlisle for encouraging us to explore this area. We are particularly grateful to James Symons and Hashem Pesaran for helpful discussions on the econometrics and comments, and grateful to Mark Rogers and Keith Maskus for helpful discussions and comments, without implicating any of them in any way in the remaining errors.

2. The criterion applied here is the global acreage of a crop.

3. All of these crops are grown both in developing and developed countries, although some are clearly more prevalent in one region than the other. For example, rice has 97 per cent of its acreage in the developing countries and millet 96 per cent. Barley has 72 per cent in developed countries.

4. This estimate gives equal weight to each country and is based on the country classification adopted in Pardey *et al.* (1991) and taken up by the wider literature on agricultural R&D. A comparison of yields on an area–weighted basis directly based on FAO data and its classification of developing and developed countries produces an even more dramatic picture while leaving the ranking of crops basically unaffected (see Goeschl and Swanson, 2002).

5. For example, recent work has demonstrated a general relationship between climate and development status. (Masters and Sachs, 2001). It might be argued on the basis of such evidence that climatic conditions systematically favour production within developed countries (often in temperate zones) over developing ones (often in tropical zones). This study includes agro–ecological conditions, but the authors believe that the primary factors of concern should relate in some clear manner to the transferability of technical change.

6. This paper thus falls in the theoretical line established by Krugman (1979) and leading to Lai (1999), but its approach is empirical. The distributional implications of the arguments are more fully simulated and expounded in Goeschl and Swanson (2000).

7. The argument presented here does not rule out that other factors impinge on the transferability of innovations in agricultural technology, such as agro–ecological factors or crop–specific complementary inputs biased against developing countries. These are the points commonly put forward to explain this diversity of gaps. By abstracting from these factors, this paper points instead to a broader problem in the area of agricultural R&D, namely the conflict between stimulating an optimal amount of R&D and ensuring optimal diffusion of the resulting innovations.

8. This distinction between strong and weak property right regimes is delineated further on page 61.

9. The $\psi(1)$ is sufficiently large in order to prevent the possibility of total imitation in the limit and the $\psi(0)$ is sufficiently small that there is a minimum of imitation going on at any point in time.

10. In 1991, agricultural R&D expenditures in 131 developing countries combined were 8 009 million 1985 international dollars and in 22 developed countries combined $6 941 million. For 1981, the data were $5 503 million and $5 713 million, and for 1971 $2 984 million and $4 298 million respectively (Alston *et al.*, 1998). Thus, over the entire period, R&D expenditures were of roughly comparable size.

11. The term "frontier" refers to the outer margin of production possibilities at a given time. In the given application, it refers to the best yields achievable in a given year.

12. See endnote 4. The growth rates in developed countries are a sufficiently accurate representation of yield growth at the frontier and a more robust estimate than the maximum yield achieved by whichever country. The problem with the latter method is that it suffers from *1)* sampling error (the observations in 1961 and 1999 are realisations of some random process), and *2)* measurement error (the FAO data are not fully reliable). The maximum yield method puts a lot of weight on an individual year/country observation and makes it unsuitable for drawing conclusions from it.

13. Rice may be somewhat an exception as it started out from relative high yield levels in 1961 of five tonnes per ha.

14. The favourite explanation along these lines is the agro–ecological hypothesis. It claims that yield gaps exist because developing countries are situated in climate zones that feature adverse production conditions. The suitability of a crop for use in developing countries would thus be inversely related to the productivity gap observed. This hypothesis is dealt with again later.

15. The country yield data suffer from several deficiencies. The most obvious is that they do not appear particularly reliable for some countries. Fortunately, this tends to be more the case the smaller the production. Another is that some crops were introduced into countries only during the observation period. Here the rule is adopted that only those countries that cultivated the crop in 1961 should be included in the sample, because adopters are likely to under–perform at early stages of cultivation and thus to bias the estimation. For soybeans, this led to a fairly high number of discarded observations.

16. The presence of heteroskedasdicity tends to lead to higher diffusion coefficients. This weighting procedure corrects for that. The White test for cross–section heteroskedasticity is performed for all estimations and reports consistent parameters for all crops.

17. The curve is fairly robust against changes in the discount rate. A higher rate pushes the curve down slightly, and *vice versa*.

18. There are for each crop countries in which the intrinsic growth rate of the yield is basically equal to or above that prevalent in the frontier countries. For barley, this holds in Zimbabwe; for cotton, in Israel and Syria; for maize, in Chile; for millet, in China; for rice, in Egypt and Korea; for sorghum, in Egypt and Israel; for soybeans, in Ethiopia; and for wheat, in Egypt and Zimbabwe.

19. The correlation coefficient between $\hat{a}$ and β is 0.02.

20. The authors also investigated the importance of increased allocations of land and of agro–ecological circumstances, and found these factors to be either of no significance or much lower impact than the factors discussed here.

21. The so–called UPOV convention provides that each member state should provide property–right protection in innovative plant varieties. It is also possible to take traditional forms of patent rights in innovative seeds.

22. Maskus (2001) cites two types of evidence for this proposition. First, there is the generally observed positive correlation between national income and adoption of IPR regimes. Second, there is the positive correlation between national income and perceived effectiveness of such regimes, as demonstrated in the World Economic Forum's surveys of perceived strength of IPR enforcement (the index for 21 developed countries is 50 per cent greater than that for 18 developing countries).

23. An interesting future issue is the impact of technological change that affords technological protection to other crop species, the so–called genetic use restriction technologies, and the welfare implications for various countries (Goeschl and Swanson (2000).

24. For observations involving hybrid crops, $D=1$.

25. See endnote 17.

Bibliography

ALSTON, J.M. AND R.J. VENNER (1998), "The Effects of the US Plant Variety Protection Act on Wheat Genetic Improvement", paper presented at the symposium on "Intellectual Property Rights and Agricultural Research Impact", sponsored by NC 208 and CIMMYT Economics Program, El Batan, Mexico, March 5–7.

ALSTON, J.M., P.G. PARDEY AND VINCENT H. SMITH (1998), "Financing Agricultural R&D in Rich Countries: What's Happening and Why?", *The Australian Journal of Agricultural and Resource Economics* 42(1).

BARRO, R., AND X. SALA–I–MARTIN (1995), *Economic Growth*, McGraw–Hill, New York.

EVENSON, R. AND Y. KISLEV (1973), "Research and Productivity in Wheat and Maize", *Journal of Political Economy*, 81(6).

EVENSON, R., P.E. WAGGONER AND V. RUTTAN (1979), "Economic Benefits from Research: The Case of Agriculture", *Science*, 205.

GOESCHL, T. AND T. SWANSON (2002), "Diffusion and IPR Regimes in Biotechnology", *in* T. SWANSON (ed.), *Biotechnology, Agriculture and the Developing World. The Distributional Implications of Technological Change*, Edward Elgar, Cheltenham.

GOESCHL, T. AND T. SWANSON (2000), "Genetic Use Restriction Technologies and the Diffusion of Yield Gains to Developing Countries", *Journal of International Development,* 12.

GRILICHES, Z. (1957), "Hybrid Corn: An Exploration in the Economics of Technological Change", *Econometrica* 48.

HSIAO, C. (1986), *The Analysis of Panel Data*, Econometric Society Monographs No. 11, Cambridge University Press, Cambridge.

KRUGMAN, P. (1979), "A Model of Innovation, Technology Transfer, and the World Distribution of Income", *Journal of Political Economy,* 87.

LAI, E. L.–C. (1998), "International Intellectual Property Rights Protection and the Rate of Product Innovation", *Journal of Development Economics*, 55(1).

MADDALA, G.S. AND S. WU (1999), "A Comparative Study of Unit Root Tests with Panel Data and a New Simple Test", *Oxford Bulletin of Economics and Statistics*, Special Issue.

MASKUS, K.E. (2000), *Intellectual Property Rights in the Global Economy*, Institute for International Economics, Washington, D.C.

MASTERS, W.A. AND J. SACHS (2001), "Climate and Development", Paper presented at the 2001 American Economic Association Meeting, New Orleans.

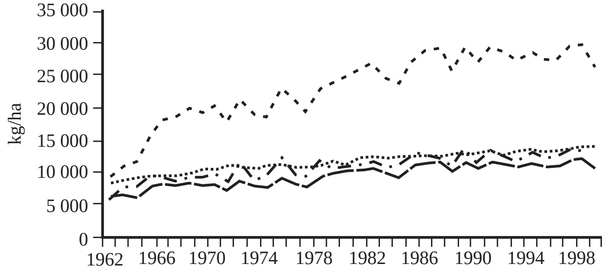
PARDEY, P.G., J. ROSEBOOM AND J.R. ANDERSON (eds.) (1991), *Agricultural Research Policy: International Quantitative Perspectives*, Cambridge University Press, Cambridge.

ROMER, P. (1990), "Endogenous Technological Change", *Journal of Political Economy*, 98 (5).

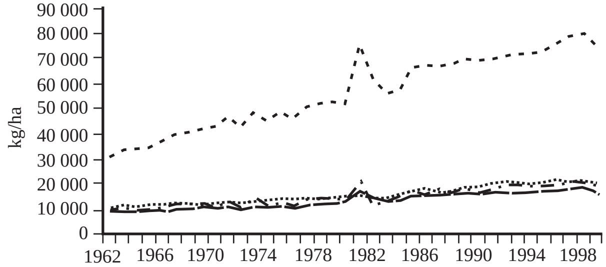
SCHMITZ, A. AND D. SECKLER (1970), "Mechanized Agriculture and Social Welfare: The Case of the Tomato Harvester", *American Journal of Agricultural Economics*, 52.

ZILBERMAN, D. AND A. HEIMAN (1997), "The Value of Economic Research", *American Journal of Agricultural Economics* 79(5).

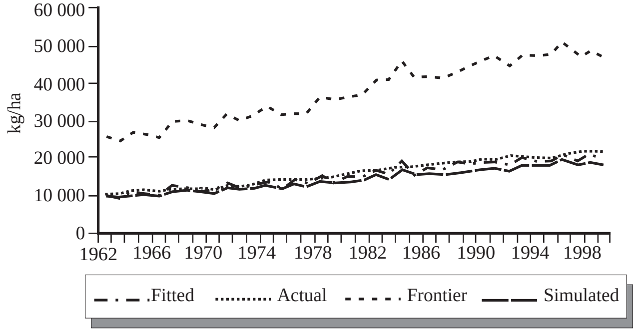
Annex A. **Actual, Fitted and Simulated Yield Developments in Developing Countries**



Development of Cotton Yields, 1962-1999

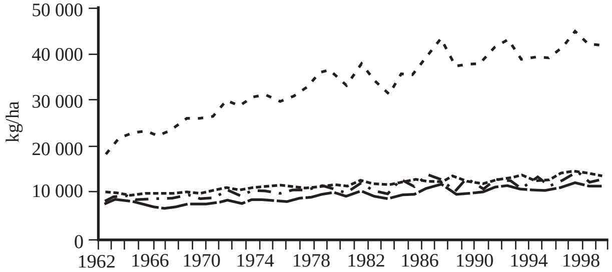


Development of Maize Yields, 1962-1999

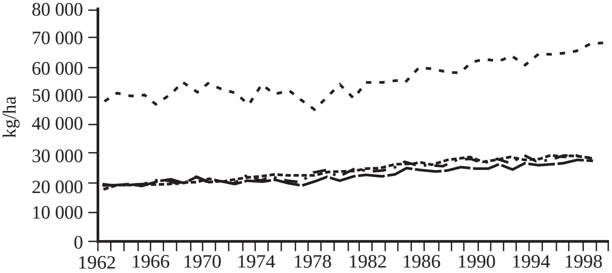


Development of Wheat Yields, 1962-1999

Development of Sorghum Yields, 1962-1999



Development of Rice Yields, 1962-1999



Development of Soybean Yields, 1962-1999