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The development impact of genetic use restriction technologies: a forecast based on the hybrid crop experience

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ABSTRACT. Advances in biotechnology have made available gene-manipulation techniques that enable the protection of genetic material from unauthorized use and the prevention of self-supply of commercial seeds by farmers—in order to allow enhanced appropriation of the values of innovation in agricultural R&D. These techniques have become known as Genetic Use Restriction Technologies (GURTs).

This paper forecasts the potential impact of wide-spread adoption of GURTs by the providers of HYV seeds on the yield development in developing countries. To do so, it assesses (1) the effects of enhanced appropriation through GURTs on the technological expansion at the yield frontier and (2) the effects of technological protection of value-adding traits through GURTS on the diffusion of yield gains from the frontier to developing countries. These assessments are based on a particular hypothesis, which is that GURTs will replicate across most staple crops the experiences that were made with a previous use restriction technology (hybridization) in only a few crops. The estimation of impacts is carried out as a simulation and is based on expansion and diffusion parameters estimated for hybrid seeds over a 38-year period. It shows that the impact of GURTs on developing countries' yields will vary considerably. Specifically, those countries that currently have the lowest yields would be most adversely affected in their future yield development by the wide-spread use of GURTs.

1. Introduction

There is a general expectation among proponents of biotechnological modification of crops that advanced techniques of genetic manipulation in

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plants will significantly enhance agricultural productivity. Concurrently, this technological development has delivered the means of protecting the genetic information responsible for these productivity improvements against unauthorized reproduction and extraction. These technologies have been termed 'genetic use restriction technologies' (GURTs) in reference to the control of unauthorized use of the novel genetic structure that delivers improved traits.[1]

Although still at the patent stage, there are several areas of concerns about the potential implications of GURTs. Some observers worry about the environmental effects of geneflow from crops thus sterilized to other plants, causing the potential sterilization of seeds beyond the confines of the individual field (Jefferson, 1999; Crouch, 1998). The distribution of economic rents between farmers, seed companies, and consumers is another area of possibly undesirable consequences (Srinivasan and Thirtle,. 2000). Others are concerned about the impacts of these technologies on the livelihoods of subsistence farmers who predominantly rely on saved seed for replanting their fields (RAFI 1999). The focus of this paper is the analysis of GURTs from the perspective of agricultural productivity growth through crop-improving innovations and the diffusion of these innovations to developing countries.

This focus situates the problem in the context of economic development and agricultural R&D. In the management of the research and development (R&D) process, society is attempting to solve a particular form of a public goods supply problem. The information generated by the R&D process has the character of a public good, i.e. it is non-rival and non-excludable. In the absence of regimes that ensure a flow of rents to the creator of this information, its public good character poses a strong disincentive for private investment in R&D. The rationale for the creation of property rights in innovations is that such regimes will have the effect of encouraging investments in R&D, and hence the supply of information resulting from it. Plant breeding forms an essential part of R&D in the agricultural sector. It has been shown to be a major source of agricultural productivity growth (Traxler *et al.*, 1995; Huffman and Evenson, 1993; Schmidt, 1984; Thirtle, 1985; Evenson and Kislev, 1973). At the same time, plant breeding poses an even more formidable problem to society than usual R&D processes because the R&D output, namely seeds, has a self-reproducing property. This makes it very difficult for the innovator to control the dissemination of innovative traits. Additionally, cross-breeding offers competitors the potential for accumulating others' innovations within their own R&D output. In essence, the ease of transfer of traits between crops makes it very hard to protect the proprietary information contained in improved varieties (Swanson, 1996). The result is that in the absence of intellectual property rights, very little private R&D would be carried out in plant breeding in comparison to the social benefits that are generated through such crop improvements.

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[1] In the general public, they have become better known by the name 'terminator genes'. This epithet was coined by Rural Advancement Foundation International, an NGO; 'traitor technology' has been another suggestion.

The fundamental idea is that GURTs represent a novel mechanism for appropriating the rents from innovation in the plant breeding industry. This mechanism radically enhances the plant breeder's scope for rent capture. This is likely to result in increased private investment into agricultural R&D and hence in a higher rate of innovation in the plant breeding industry. On the other hand, a consequence of this novel mechanism is that it significantly complicates the dissemination of crop improvements through adaptive breeding and informal seed trade.

Technologies that inhibit the dissemination of innovations are likely to have adverse impacts on countries for which innovations created abroad are the major source of crop improvement and that are therefore dependent on access to this flow for productivity increases.[2] Among these countries are the least developed of the world (Coe, Helpman, and Hoffmaister, 1997). One of the possible consequences of GURTs is hence that they may lead to a distinct downward shift in the growth trajectories of agricultural productivity in developing countries. This downward shift would work in the opposite direction of the potential increase in private R&D for crop improvement stimulated by GURTs. It would be caused by restrictions in the flow of innovations to which developing countries have had access over the period of pronounced yield growth in the last 50 years. If this restriction outweighs the effect of increased R&D, then developing countries are likely to face cumulative losses in agricultural productivity growth as a result of widespread adoption of GURTs by crop innovators.

How can the possibility of this link between GURTs and a reduction in the rate of diffusion be substantiated? In this paper, we draw on the experiences with a previous use restriction technology in agriculture in order to establish that the mechanism for rent appropriation in agricultural R&D has measurable effects in terms of both the rate of innovation at the technological frontier and the rate of diffusion from the frontier to developing countries. This empirical evidence allows us to make simulation-based inferences regarding the probable impact of GURTs on developing countries and on the diversity of experiences that this technology will bring about among these countries based on structural differences in their capacity to capture the flow of innovations.

Although GURTs are of recent origin, technologies with similar characteristics have existed for many decades, specifically the hybridization of cultivated varieties. This technique has been available for commercial seeds since the 1920s. Hybridization of cultivars has two implications. One is that the replanting of seeds from a hybrid results in a rapid deterioration of yield potential.[3] The other is that it protects against unauthorized reproduction by farmers and that the composition of the hybrid can be withheld from other breeders if the innovator does not disclose the inbred lines that make up the hybrid crop. GURT crops share these two characteristics with hybrid crops, albeit in more extreme forms: replanting of GURT seeds

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[2] The National Agricultural Research Centres (NARCs) and the CGIAR system currently provide mechanisms for facilitating this flow of innovations through adaptation of advanced material to local condition (Pardey et al. 1991).

[3] The first-generation loss is normally in the order of 25–30 per cent.

results in an expected yield loss of close to 100 per cent, and the reproduction of the crop's underlying genetic structure by a third party is currently not feasible since reproduction of the seed itself is impossible (DFID, 1999). The application of hybridization in the commercial seed sector also suggests that the availability of use restriction through this technique has been widely used by private companies when investing in R&D in those crops in which hybrids are feasible (Marion and Butler, 1984; Butler, 1996). This means that hybrid crops share fundamental features of use restriction with GURTs (although these features operate to different degrees of perfection in these two applications) and that industry has made significant use of these features as a form of rent protection.

In a previous paper (Goeschl and Swanson, 2000), we have estimated the rate of diffusion of innovations in hybrid and non-hybrid crops over the last 40 years. These estimates can be regarded as indicative of the likely impacts of the adoption of GURTs by crop innovators. Here we use these estimates as the basis for forecasting what probably constitutes the lower bound on the impact of GURTs in developing countries. These impacts are expected to arise out of the application of GURTs to those crops for which hybridization is currently not carried out on a significant scale, such as wheat and rice.

The remainder of the paper is organized as follows. The following section reviews the results of a 39-year panel study of yield developments in the most important hybrid and non-hybrid crops. In section 3, we then apply these results in order to forecast the yield development in currently non-hybridized crops in selected countries. The likely development in the absence of GURTs, i.e. a perpetuation of the current regime, is then compared with the expected growth of yields when GURTs are widespread. In section 4, we discuss the nature and robustness of the results. In the concluding section, we relate these results to the question of a global system of intellectual property protection for agricultural R&D.

2. Review of panel study on diffusion

In this section, we survey the results of a panel study on yield development in the eight most widely cultivated crops,[4] barley, cotton, maize, millet, rice, sorghum, soybeans, and wheat covering 39 years, from 1961 to 1999. For a full description of the data, econometric methodology, and modelling, we refer to (Goeschl and Swanson, 2000 and forthcoming). In the past, use restriction has been crop specific: in two of the eight crops, namely maize and sorghum, the vast majority of improved varieties are hybridized. In the remaining six, hybridization is rare. This crop specificity enables us to compare the performance of hybrid and non-hybrid crops with respect to diffusion.

The method used is a fixed-effect panel estimation model that allows for heterogeneity among the countries through variable intercepts (Hsiao, 1986). The specific model that is being estimated is common in the empirical estimation of productivity convergence in other sectors and widely used in the literature on economic growth (Barro and Sala-i-Martin,

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[4] The criterion applied here is the global acreage of a crop.

1995).[5] This literature considers the diffusion of technology as a continuous process of innovations occuring at the productivity frontier and subsequently diffusing to developing countries.[6] This process is modelling as a sequence of exogenous stochastic shocks, i.e. the event of an innovation, that sets countries back in their relative yields in comparison to the technological frontier.[7] We 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 this shock is compensated for, allowing for heterogeneity in the intrinsic 'rate of recovery' between countries. The model has the form

$$\Delta G_{it} = \alpha_i + \beta \cdot G_{i,t-1} + \gamma \cdot D \cdot G_{i,t-1} + \epsilon \tag{1}$$

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. 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 are responsible for the disproportionate yield gap that exists in the case of maize and sorghum. The coefficient β that is to be estimated then reports the diffusion coefficient across all crops and γ is the diffusion rate differential for hybrids crops identified through the dummy variable D.[8] Empirically, we perform Fisher's test as proposed by Maddala and Wu (1999) as a panel data unit root test. We then estimate the diffusion coefficient β and the diffusion rate differential γ according to equation (2) as a GLS-regression correcting for the residuals being cross-section heteroskedastic by down-weighting each pool equation by an estimate of the cross-section residual standard deviation.[9]

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[5] For a full development of the model in the context of fixed effects such as agro-ecological factors, see Goeschl and Swanson (2000).

[6] This type of analysis has to be contrasted with earlier studies of technological change such as Griliches (1957) where a discrete innovation is examined as it intertemporally and spatially diffuses from its origin.

[7] The yield data for the eight crops examined are annual yield data from the FAO Statistical Database (FAOSTAT). The data record the harvested production per unit of harvested area for crop products based on the annual harvest data and the area harvested. Data are recorded in hectogramme (100 grammes) per hectare (HG/HA). The data are not always fully reliable. Specifically, all countries were omitted for which no complete time series of yield data was available for the 39-year period or whose yield data showed an obvious lack of reliability. Even with a stringent application of these the country classification developed in (Pardey et al 1991) and taken up by the wider literature on agricultural R&D.

[8] For observations involving hybrid crops, $D = 1$.

[9] The presence of heteroskedasticity 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.

Econometric results

The estimation delivers coefficients β and γ that are statistically highly significant. We also report the *average* intercept for all countries in the estimation denoted by $\hat{a}$. Before interpreting the results, it is convenient to perform some algebra in order to bring the model into a simpler form. Rearranging (1), we arrive at the following equation for the growth rate of yield, $\Delta\hat{y}_{\mathrm{t}}$, in the average developing country

$$\Delta\hat{y}_{\mathrm{t}} = \Delta y^*_{\mathrm{t}} - (1 + \beta + \gamma \cdot D) \cdot G_{t,t-1} + \hat{a} + \epsilon \tag{2}$$

This formulation highlights the separate components that drive the growth rate of yields in the average developing country. The first component is the yield gain at the frontier Δy^*. This reflects the expansion of the set of technological possibilities. The second component captures the extent to which an innovation can diffuse in the country. We define the gap G to take on positive values. Therefore, we 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 hybridization on the growth rate. The fourth parameter, $\hat{a}$, sumarizes 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.

Interpreting the results: diffusion

Table 1 shows the results of the econometric estimation of equation (1). The most important result is that hybridization 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 demonstrates that roughly 69 per cent of the gap opened by an innovation is carried over into the next year. The 'diffusion penalty' involved in having innovations predominantly occur in hybridized crops is about 7.1 per cent per year. This means that developing

Table 1. *Regressions for diffusion of innovations in different crops*

Coefficient	
β[10]	−0.313 (0.008)***
γ	0.071 (0.011)***
α	−0.33611
R^2	0.16
(number of observ.)	(14858)
DW-statistic	2.39

Notes: The figure in parentheses is the standard error. * Indicates significance at the 5 per cent level, ** at the 1 per cent level.

countries retained about 7 per cent more of the yield gap each year in hybrids than in non-hybrids. This explains an important part of the cumulative yield gap that has developed in hybrids. The results also indicate that there is merit to 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, 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 (Swanson 2002a).

The results on the rate of diffusion have an intuitive economic interpretation. For a farmer cultivating different crops, an important criterion for evaluating crops is the loss of yield suffered as a result of slow diffusion. This loss can be assessed as the present value of the cumulative process of an innovation arriving at developing countries in a delayed fashion rather than arriving immediately.[10] Figure 1 reports the multiplier to the initial shock in order to estimate the present value of the loss at a 10 per cent discount rate.[11] The interpretation of the figure is as follows: consider an innovation at the frontier in period 1 that results in an increase in profits by, say, 100 dollars for the average farmer. Within this period, the farmer in the developing country does not receive any of the innovation, thus incurring a loss of 100 dollars. In the next period, the first benefits start to

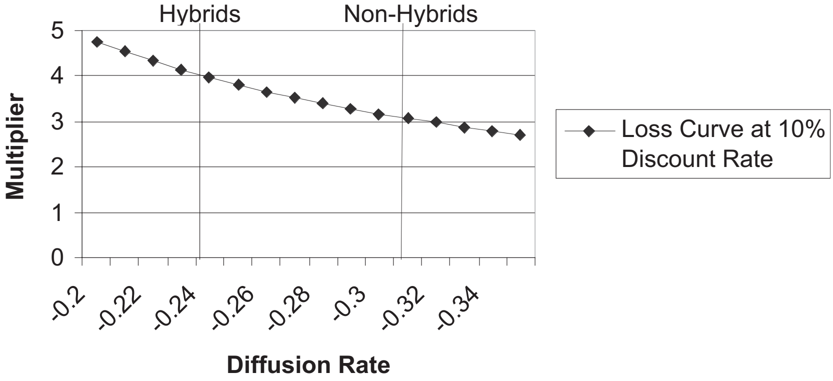

Figure 1. *Loss multiplier as a function of the diffusion rate*

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[10] This curve is constructed on the assumption that the demand curve for agricultural output has constant and equal demand elasticity in the developed and the developing countries.

[11] The curve is fairly robust against changes in the discount rate. A higher rate pushes the curve down slightly as future losses have a lower value, and vice versa.

trickle down from the frontier, thus decreasing the loss relative to the frontier, with more of the benefits becoming available in subsequent periods. The curve depicts the present value of the total accumulated losses as a factor that can be applied to the initial 'loss'. Figure 1 shows the economic loss of the frontier shifting away from the developing country by virtue of an innovation at the frontier as a function of the rate of diffusion. Based on the parameters estimated for hybrids and non-hybrids, the discounted cumulative loss in the case of hybrids is about four times the initial shock while for non-hybrids it is around three times. This implies cumulative losses being about a third higher in hybrids as opposed to non-hybrids.

Interpreting the results: country-specific lags

A second set of important differences arises from the country-specific data on 'individual growth capacity'. The first result is that, on average, developing countries would experience slower growth in all crop yields as the coefficient $\hat{a}$ is below zero for all crops. However, these impediments to growth are quite different between crops, ranging from rice, a crop with good intrinsic growth potential in developing countries, at $\hat{a} = -0.230$, to wheat, with high average barriers to growth, at $\hat{a} = -0.384$. This captures whether innovations have been diffusing to countries where the local conditions are beneficial or adverse to the successful cultivation of the plant.[12] Interestingly, 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.[13]

3. Forecasting the impact of genetic use restriction technologies

With respect to its impact on the unauthorized reproduction of advanced cultivars, hybridization is a technological precursor of genetic use restriction technologies. It shares fundamental features with GURTs, although these features are exhibited in GURTs to a higher degree of 'perfection' than in hybrids.

Crops that have so far not been marketed as hybrids are the most likely target of genetic use restriction technologies (DFID, 1999). It will be in these crops, therefore, where the impact of GURTs will be the most significant as the regime of intellectual property protection will shift from an essentially public domain provision to a use restricted regime. On the basis of the empirical estimates on hybrids, we carry out some forecasts regarding the likely impact of adopting use restriction technologies in these crops.

Baseline scenario and parameters

The panel study reported is based on a leader–follower framework of innovation and diffusion (Barro and Sala-i-Martin, 1995). The simulation

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

[13] The correlation coefficient between $\hat{a}$ and β is 0.02 across all crops.

extends this framework into a forecasting situation where the three components determining the growth of yields in the developing country are the expansion at the frontier, the rate of diffusion from the frontier to the developing country, and the long-term differences in growth rates in crop yields. The baseline scenario for this forecast is the continued absence of GURTs from seed production. This baseline is established by assuming a perpetuation of the estimated growth rate at the frontier and rate of diffusion from the frontier. We refer to the baseline as the scenario 'in the absence of use restriction'.

The experience from hybrid crops suggests that expansion at the frontier will benefit from increased scope for rent capture by stimulating private R&D (Srinivasan and Thirtle, 2000). We therefore assume that the rate of expansion at the frontier will be higher in the presence of GURTS. This is important because it implies that *ultimately* every developing country's yields will be higher under use restriction than under the continuation of the present public domain regime. This underlines the importance of GURTs providing private industry incentives for the long-term development of yields. Due to the presence of a discount rate, however, the welfare effects of GURTs are not time-invariant. The crucial question is *how long* it takes for yields under GURTs to overtake the baseline scenario without use restriction. This is determined by the rate of diffusion, the country-specific long-term deviation from the growth rate at the frontier and the current gap in yields between the individual developing country and the frontier.

Our forecasting simulation looks at a 20-year time horizon for the development of yields in non-hybrids crops under the two scenarios. In order to simplify the comparison, the average values of the six non-hybrid crops are used.

For the productivity frontier, we assume a starting yield in non-hybrids of 4t/ha for the year 2000 in both the baseline and the use restriction scenario.[14] For the baseline scenario, we assume a continued growth at 1.58 per cent per annum in the yields of non-hybrid crops in developed countries. This is the mean of past growth rates in the six different crops at the frontier (see Goeschl and Swanson, 2000). For the use restriction scenario, we initially assume that yield growth will be take place at the rate experienced in hybrids in developed countries over the last 40 years, which has been 2.175 per cent on average (see Goeschl and Swanson, 2000). The parameters estimated through equation (1) and reported in table 1 are used as parameters for the rates of diffusion under the baseline (-0.312) and the use restriction (-0.242) scenarios. Adoption of GURT crops in developing countries is assumed not to take place as long as there are no yield benefits from the new technology.

Simulation results—all developing countries

Figures 2 and 3 show the yield histogram and yield statistics for all 86 developing countries analysed in this paper under the baseline scenario and that

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[14] The simulation is not sensitive to particular numerical yield values. The initial yield is only chosen for illustrative purposes.

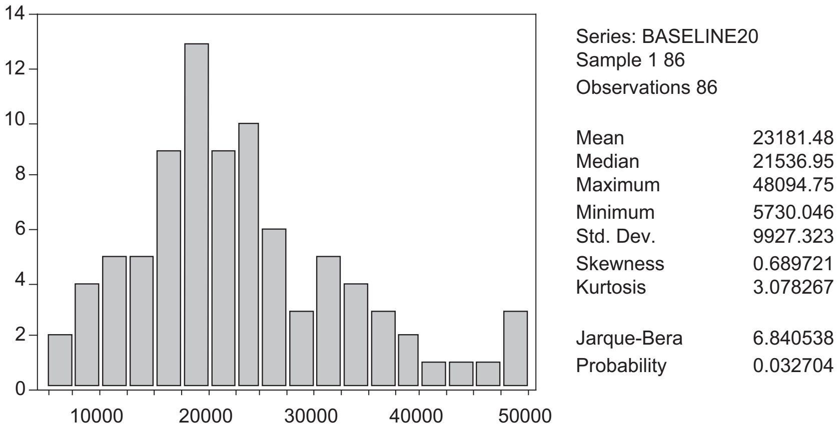

Figure 2. *Yield histogram and yield statistics for the year 2020 for 86 developing countries in the baseline scenario*

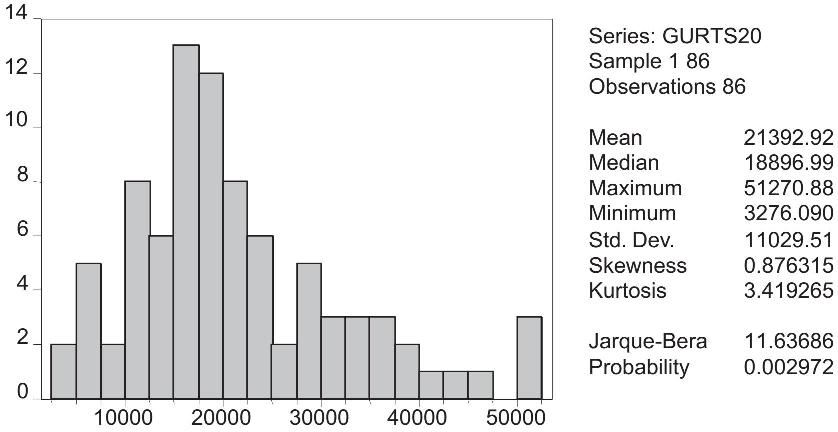

Figure 3. *Yield histogram and yield statistics for the year 2020 for 86 developing countries in the GURTs scenario*

of widespread use of GURTs in the year 2020. These figures sumarize the overall impact of GURTs relative to a continuation of the current regime.

In the absence of changes to the current IPR regime, the average yield in developing countries will be 23.1 tons per hectare at that point in time. If GURTs were adopted, average yields will be about 8 per cent (or about 2 tons) lower. By contrast, average yields in developed countries after widespread adoption of GURTs are forecast to exceed the baseline by more than 10 per cent by 2020. It is only after another 20 years, i.e. in the year 2040, that developing countries' average yields under GURTs overtake those under the baseline regime.[15]

[15] This should be taken as indicative only as the error of margin in the forecast dramatically increases from 20 to 40 years.

Table 2. *Country-specific simulation parameters*

	China	*Ethiopia*	*Tanzania*
Average yield in non-hybrids in per cent of developed country yield	85.1%	56%	25%
Average country-specific long-term deviation from developed countries' growth rate in non-hybrids	−0.094	−0.2128	−0.338

Another aspect are the distributive effects of GURTs between developing countries. One indicator of this is the coefficient of variation in yields across developing countries. In the baseline scenario, this coefficient is 0.42; in the case of GURTs it rises to 0.52, indicating that under GURTs differences in agricultural productivity will increase rather than decrease.

At the general level then, the two principal conclusions are therefore that GURTs tend to lead to an initially flatter growth curve and hence lower yields in developing countries over a 20 year period on average and that the variance in yields, i.e. distributive disparity, will rise.

The increasing variance in developing country yields merits further examination since it suggests that individual countries will experience very different results of an adoption of GURTs. To do this we selected three developing countries out of the 86 countries sampled in order to illustrate some of the diversity of outcomes. These countries are China, Ethiopia, and Tanzania. They were selected on the basis that all crops included in the sample are grown there, thus providing better data and that they represent the widely divergent experiences among developing countries for reasons of different agro-ecological conditions, infrastructure, and effectiveness of public agricultural research and extension.

Table 2 reports the country specific parameters that enter into the simulations. Yields in the initial period are below developed countries' yields by the average yield gap in non-hybrids. Across these six crops, China has the lowest average shortfall in yields relative to developed countries with a 15 per cent gap, while Ethiopia has a little over half the yields of developed countries. Tanzania does particularly poorly with a gap of about 75 per cent. What is also important for the simulation is the country's long-term deviation from the yield growth rate in developing countries across the six crops. These data are generated by the estimation of equation (2) on a crop and country-specific basis.

Simulation results—selected countries

Figures 4 to 7 report the simulation output graphically. The forecasts show that the individual country experiences vary quite considerably. In developed countries (figure 2), the adoption of use restriction results in higher growth rates in yield and a more favourable yield development over the 20 year time horizon. There are developing countries where the experience is similar to developed countries, but arises in a more delayed fashion: in China (figure 3) for instance, yields in the first ten years are expected to be very similar under both scenarios before the impact of use restriction on

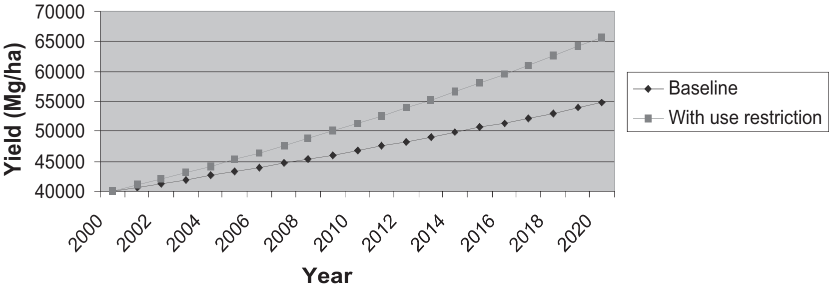

Figure 4. *Comparison of yields under the use restriction and baseline scenarios, developed countries, 2000–2020*

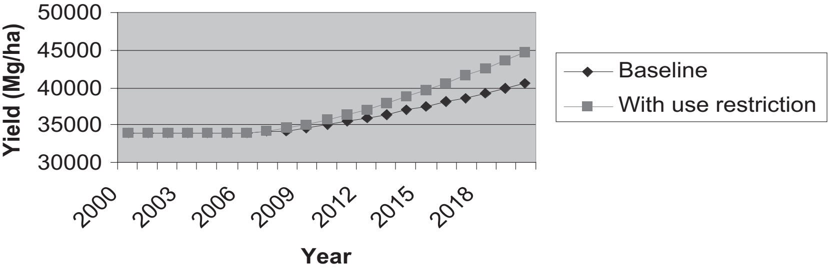

Figure 5. *Comparison of yields under the use restriction and baseline scenarios, China, 2000–2020*

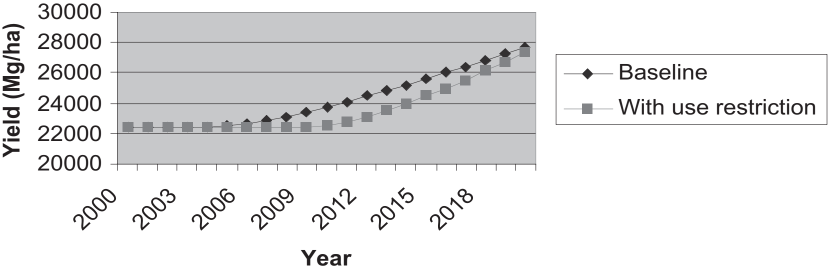

Figure 6. *Comparison of yields under the use restriction and baseline scenarios, Ethiopia, 2000–2020*

the yield frontier begins to push yields in China above the baseline. The case of Ethiopia illustrates a country that in the short run would be better off under the current regime, as the flow of innovations would be more easily appropriable. However, towards the end of the 20 year horizon, the faster expansion at the technological frontier under use restriction has compensated for the slower diffusion inherent in this regime. Lastly, the case of Tanzania illustrates a case where for the foreseeable future, the

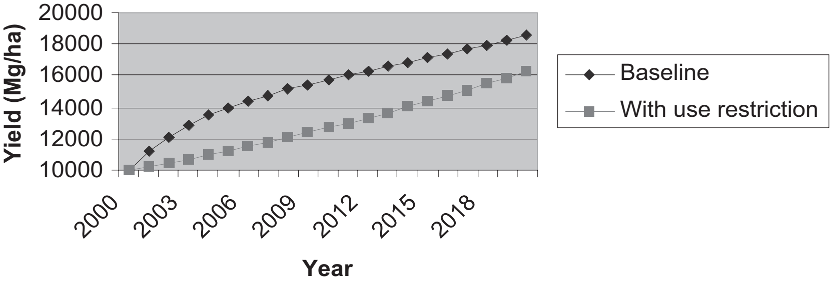

Figure 7. *Comparison of yields under the use restriction and baseline scenarios, Tanzania, 2000–2020*

country would be worse off under a use restriction scenario than under a perpetuation of the current regime.

These four cases illustrate the diversity of outcomes that can be expected as a result of a potential adoption of genetic use restriction technologies. This diversity implies that over a policy-relevant time horizon of 20 years, countries will not be indifferent as to the regime adopted, depending on the current state of a country's agriculture. The simulations suggest that the most advanced countries stand to benefit most from use restriction while the least advanced stand to lose. As stressed before, when projected sufficiently far into the future, the productivity gains that the stimulation of private R&D through use restriction result in the baseline scenario being overtaken. However, the NPV of these gains may currently be insufficient for developing countries to outweigh the short-term losses. It is interesting to note that even if GURTs led to a doubling of the rate of innovation seen in hybrids at the same rate of diffusion, it would take more than ten years in the case of Tanzania for yields under use restriction to outperform the baseline yields.

Some implications The shift in the growth trajectory that developing countries are likely to experience as a result of a widespread adoption GURTs will lead in the long run to higher yields everywhere. However, most countries, and particularly the least developed ones, will have to pass through a phase of loss relative to the present regime for the diffusion of agricultural innovations. One of the implications is that this will lead—at least in the short to medium term—to the emergence of new 'growth clubs' in agricultural development as countries will be put on different yield growth trajectories. The distributional consequences of this development over time may be considered undesirable. Another implication is that developing countries will need to develop new approaches to capturing the results of international agricultural R&D in order to maintain the flow of innovations into the country and thus to mitigate the adverse transitional period to higher yield growth. This leads to the wider question about the role of the public sector at a national and international level when use restriction technology is widespread. For some countries, such as in the case of Tanzania, new technological, contractual, and regulatory measures would be required in order to avert significant welfare losses.

Qualifications

There are a number of qualifications to this forecast, some of which are generic to any forecasting exercise, some of which are case specific. The generic qualifications are that any *ex ante* appraisal of a technology has a wide error margin as there is no observable evidence from the technology per se and that data available on antecedent technologies have their limitations. Also, the simulation describes a world where the public response to the wide-spread adoption of GURTs mirrors the historical response in the case of hybrids. This need not be the case and this simulation exercise is intended to invite policy makers to reflect on the effects of previous policy responses. Specific qualifications are that the country impacts estimated are unweighted averages across all non-hybrids. This tends to downplay the impact of crops where a country has a comparative advantage in production. The simulation also does not take into account any endogenous adjustments that might take place as a result of use restriction technology becoming available. Obvious examples would be a change in the portfolio of crops produced. It is not clear, however, whether including such adjustments would necessarily decrease the error margin. The final qualification is that the simulation is based on empirical estimates derived from a comparative study of innovation and diffusion in hybrids and non-hybrids. Although the *direction* of the impact of GURTs is likely to be the same as the impact of hybrids, the *volume* of the impact is harder to assess. Since GURTs present a more advanced form of use restriction, the impact of hybrids is likely to represent the lower bound on the impact of GURTs. Interestingly, though, the timing of the impacts illustrated by figures 2 to 5 is not significantly altered if there is a parallel decrease in the rate of diffusion when the rate of innovation increases.

Conclusion

If, as is reasonable to expect, GURTs will replicate the experiences in hybrid-based agriculture across all other staple crops, this will lead in the first instance to a higher rate of investment by private industry in crop improvement motivated by enhanced scope for rent capture. This could result in a net increase or decrease in the amount of crop improvement produced globally, depending on the degree to which this private spending will crowd out public expenditures on agricultural R&D. We have assumed for the purpose of this simulation that the rate of innovation will rise to the level experienced in hybrid crops over the last 40 years. The impact of GURTs on the rate of diffusion of these new innovations is less ambiguous. On the basis of the experiences with hybrid crops, we can predict that GURTs will negatively impact on the rate of diffusion of innovations in those crops for which developing countries could previously rely on an inflow of innovations from abroad. This is because the advanced germplasm incorporated within advanced commercial cultivars will be much more costly to extract, reproduce, and disseminate, impeding the adaptation of the latest generation of value-adding traits to local farming systems. This means that developing countries that predominantly use varieties that are currently not hybridized will experience a discontinuous shift on to a different trajectory of yield growth from the one they are currently moving along. For most countries, this implies a period of deteriorating net growth relative to the current regime. It is distributionally problematic that this period is the longest for the least developed countries. It is for this reason that GURTs present a challenge to the global regulation of biotechnologies and to the role of the public sector in generating and diffusing productivity gains (Swanson 2002a, b).

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