Macroeconomic Dynamics, **11**, 2007, 487–518. Printed in the United States of America.
DOI: 10.1017/S1365100507060166

INAPPROPRIATE TECHNOLOGY

What Is in It for the Rich?

ANA FERNANDES
University of Bern

KRISHNA B. KUMAR
Fuqua School of Business, Duke University
and
RAND

In this paper, we investigate incentives, other than altruism, that developed countries have for improving developing country technologies. We propose a simple model of international trade between two regions, in which individuals have preferences over an inferior good and a luxury good. The poor region has a comparative advantage in the production of the inferior good. Even when costly adaptation of the technology to the poor region's characteristics is required—making the technology inappropriate for local use—there are parameter configurations for which the rich region has an incentive to incur this cost. It benefits from a terms-of-trade improvement and from greater specialization in the luxury good. Indeed, there are cases where the rich region would prefer to improve the poor region's technology for producing the inferior good rather than its own. We apply our model to the Green Revolution and provide a quantitative assessment of its welfare effects.

Keywords: Technology Improvements, Dynamic Trade Models, Welfare Analysis

1. INTRODUCTION

Calls are often made on humanitarian grounds for developed countries to become actively involved in solving economic problems particular to developing countries, such as funding research on malarial drugs and AIDS vaccines for the poor countries.[1] The benefits to poor countries from improved seed varieties and vaccines might seem obvious; however, for the rich countries, is altruism the only motivation to invent or improve technologies for the poor? Under what circumstances would the industrialized world find that developing and donating technological innovations to the developing region was also in its own economic

We are grateful to two anonymous referees for their detailed comments, which have considerably improved the paper. We also benefited from useful discussions and comments from V. V. Chari, Alejandro Cuñat, Doug Gollin, Doug Joines, Larry Kotlikoff, Robert Lucas, John Matsusaka, Victor Rios-Rull, Jim Robinson, Manuel Santos, Martin Schneider, and especially Kei-Mu Yi, and participants at the SED meeting at Stockholm, Sweden, the Minnesota Workshop in Macroeconomic Theory, the Winter meetings of the Econometric Society at Washington, D.C., the Trade, Capital Flows and Aggregate Dynamics Workshop at the Federal Reserve Bank of Cleveland, and workshops at Boston University, the University of Toulouse, and *MadMac* (Madrid Macroeconomics Seminar).
Address correspondence to: Ana Fernandes, Department of Economics, University of Bern, Schanzeneckstrasse 1, CH-3001 Bern, Switzerland; e-mail: ana.fernandes@vwi.unibe.ch.

 1365-1005/07 $18.00

self-interest, even if such technologies were inappropriate for its own use? How is its welfare affected by improvements in the poor region's technology? These are a few of the questions we address in this paper.

We develop a nonaltruistic dynamic trade model of the world with two regions. Preferences are identical, and defined over an inferior ("agricultural"), labor-intensive good and a luxury ("nonagricultural" or "manufacturing"), capital-intensive good. The developing region produces only the inferior good using labor as the sole input, and the developed region produces this, as well as a luxury good that requires both capital and labor. We assume that technology is specific to a region and that the developing countries are unable to commit to future payments in return for technological assistance; consequently, technology transfers must take the form of donations.[2]

We initially abstract from the costs of technology improvements and focus on welfare analysis to highlight the basic forces at work; the cost of starting from an abundant technology base and modifying it for use in poor countries is likely to be small for the rich.[3] In a steady state in which the rich region specializes in the production of the luxury good, an improvement in the poor region's technology makes the terms-of-trade more favorable for the rich and increases that region's welfare. The poor benefit from increased output, but are hurt by the terms-of-trade effect; there are parameter configurations for which the net effect from better technology is beneficial to this region also. When the rich region produces both goods, an improvement in the poor region's technology induces reallocation of the rich region's labor force toward the luxury good and increases its welfare. In the specialization case there is no factor reallocation effect; here there is no improvement in its terms-of-trade. The poor region's income experiences a direct increase. One interesting result is the following: given the nonrival nature of technology and the resulting scale effect, for a large enough workforce of the poor region, the rich region benefits more from an improvement in the trading partner's agricultural sector (the *in*appropriate technology) than its own (an appropriate technology).

We then study costly technological improvements. Although these costs might not be quantitatively important, explicitly modeling them allows us to analyze the technological investment choices individual regions face, and compare them with each other. With specialization, the rich country would invest more in the poor country's technology than the poor would do on its own. The ensuing terms-of-trade increase would benefit the rich. Without specialization, under reasonable conditions, it is the poor that would invest more than the rich. The rich region experiences no improvement in its terms-of-trade here. The rich country's preference for inappropriate development is shown to be robust to the inclusion of costs.

The above-mentioned dichotomy between improved terms-of-trade and increased production becomes less stark when we analyze the transition from a low level of technology in the poor region to a higher one. For instance, when the rich region is not specialized, there is a terms-of-trade improvement during the transition even though there is none in the steady state. Modeling the dynamics allows us to gain this and other insights. It shows how capital accumulation amplifies the factor allocation effect when there is no specialization. And, as will be seen in Section 2.3, dynamic considerations make the possibility of the rich region improving an *in*appropriate technology more likely. Characterizing the dynamics also sets the stage for welfare analysis that includes transitions.

Though the model allows us to address issues of broader interest, the Green Revolution appears to be a natural application for it. The establishment of the Consultative Group on International Agricultural Research (CGIAR) in 1971 solidified international efforts in this regard that had begun as early as the 1940s. The cost of such research, although not insignificant, was not particularly high. Evenson and Gollin (2001) report that the funding for the CGIAR has been about 5 billion U.S. dollars since 1971, and its budget for 1998 was $340 million. The achievements of this revolution have been staggering.[4] As an illustration of our dynamic analysis, we provide a quantitative assessment of the welfare effects of the Green Revolution using numerical simulations. We find positive welfare benefits for both the poor and the rich regions in most cases, with the relative magnitudes of the gains mirroring the theoretical analysis summarized above.

It is well understood that a technology improvement in the poor region's export sector benefits the rich region, and that the terms-of-trade and the minimum consumption requirement are important for the welfare calculations for developing countries. However, our paper adds several novel dimensions to these results. We apply these themes to the issue of technology transfer instead of donation of goods, shifting attention from more conventional foreign aid to donation of technologies.[5] We also characterize investments in inappropriate versus appropriate technologies by the rich. Our use of a dynamic trade model allows us to compare transition path results to steady state results. The quantitative application of our model to the Green Revolution is also novel, particularly our emphasis on the incentive that *rich* countries have for improving the technology of the poor. Most of the previous work has focused on the benefits to poor countries. Finally, there is a case here against certain types of patent protection or against laws that deter technological imitation. In the simplest scenario, where the technology of the rich could be directly used by the poor, the representative consumer of the rich region would want to make the blueprints for the export sector of the poor available right away.[6]

There is an extensive literature on how a country can balance the consumer distortion arising from a tariff with increases in producer surplus and revenues and arrive at an optimal tariff. However, unlike technology improvements, optimal tariffs will hurt the poor region. Optimal tariffs are difficult to implement in practice, given the possibility of retaliation and the inefficiencies in disbursing the collected tariffs. We analyze the case without trade distortions and only briefly consider tariffs in Section 5.

Rivera-Batiz and Romer (1991) are also interested in the effects of economic integration and technological progress. However, they focus on the pure scale effects of integration and "do not consider the general case of trade between countries with different endowments and technologies," as we do. In Matsuyama

(2000), "North," which specializes in higher income elasticity goods, cannot lose from an improvement its own productivity, whereas "South," which specializes in lower elasticity goods, may lose from an improvement in its productivity. The possibility of such immiserizing growth can be traced back to Bhagwati (1958). Our model has a simpler goods structure than Matsuyama's. Moreover, the difference in income elasticities is not necessary for our results, merely amplifying the incentives of the rich region. The nonspecialized and specialized regimes we study provide a useful dichotomy in understanding the roles of increased production and improved terms-of-trade in the expansion in value of the rich region's overseas markets. Immiserizing growth will not take place in our framework, provided the negative terms-of-trade effect experienced by the poor is dominated by the higher income generated by the improved technology.

Basu and Weil (1998) model technology improvements as being specific to a given capital-labor ratio in order to explain their slow diffusion across countries. Acemoglu and Zilibotti (2001) quantify the international differences in productivity and output arising from a mismatch between rich-country technologies and poor-country skills. In these papers, the frame of reference for *in*appropriateness is the poor country; in ours it is the rich country. The mismatch they document further justifies the need for technology development directed toward poor countries. Desmet (2002) notes that transferring a new technology to a poor region that does not have the complementary old technology does not spur development. We consider the case of the rich region transferring technology appropriate to the poor region but inappropriate to itself. Baxter (1992) constructs a model in which reproducible capital, constant-returns-to-scale production, and optimizing agents can turn a standard Hecksher-Olin model into essentially a Ricardian model with specialization in the long run. We have both Ricardian and Hecksher-Olin features in our framework, and high enough agricultural productivity in the poor region can result in long-run specialization by the rich.

Given the likelihood of Pareto improvement, why are such international "interventions" rare? We have considered regions and ignored the individual countries that form a region. The free-riding problems inherent in technology improvement are likely to be a major disincentive for a given rich country to improve a poor region's technology on its own: countries that do not share the cost of research will also benefit. The issues of how sovereign entities form consortia to ensure the provision of this "public" technology, and why certain provisions such as improved crop seeds met with better success than the currently debated provision of life-saving drugs, are interesting in their own right and are the subject of ongoing research. However, in this paper we abstract from such considerations and assume that rich countries effectively coordinate their actions and can be treated as a region. We focus instead on the first step of analytically and quantitatively assessing the benefits, if any, of such a provision, and on the mechanics of trade and the transition that ensues.

The rest of the paper is structured as follows. In Section 2, we present the model and characterize steady state outcomes when the developed region produces both goods as well as when it specializes in the luxury good, when the cost of improvement is assumed away. In Section 3, we conduct the steady state welfare analysis when technology improvement is costly. We characterize the transitional dynamics that follow technology improvements in Section 4. In Section 5, we present a quantitative assessment of the welfare effects by viewing the Green Revolution through the lens of our model. Section 6 concludes.

2. THE MODEL

We consider a world with two regions—developing, or poor, subscripted by P, and developed, or rich, subscripted by R—whose citizens value consumption of two goods, denoted by superscripts 1 and 2. The instantaneous utility is given by

$$\theta \log\left(c_i^1 - m_i\right) + (1-\theta)\log\left(c_i^2\right),$$

for region $i = $ P, R. The constant $m_i > 0$ is the minimum amount of good 1 that must be consumed by region i. This good can be thought of as a necessity; it is straightforward to show that the income elasticity of demand is smaller than one for good 1, and greater than one for good 2.[7] The degree of inferiority is increasing in m_i.[8] The weight of good 1 in the overall utility is θ. It is not strictly correct to think of a “region” as an individual “country”; however, for simplicity, we will use the two terms interchangeably.

We are interested in specifying a production structure that is tractable for dynamic analysis, while capturing the key incentives the rich region has for improving the poor region’s technology. Our investigation of a simple static framework, where the inferior good is labor-intensive and the luxury good is capital-intensive, yields the following results:[9]

If the rich country has a comparative advantage in the production of good 2 (given endowments and technologies), it would prefer an improvement in the poor country’s technology for good 1 rather than good 2. The rich country benefits from an improvement in its terms-of-trade when good 1 is improved.

If the rich country’s *own* technology for good 1 improves, it directly benefits from an increase in its output as well as from an improvement in its terms-of-trade. However, if the poor country is a large enough producer of good 1, and the rich of good 2, the terms-of-trade effect is stronger if the poor country’s technology improves. This would give the rich region an incentive to improve an *in*appropriate technology rather than its own.

The rich region prefers an improvement in the poor country’s technology for good 1, say through improved crop seeds, to an improvement in its labor supply, say through drugs that treat tropical diseases. The poor region would allocate some of the increase in labor to producing good 2 and compete with the rich country, numbing the impact on the terms-of-trade. The rich region therefore prefers improvements in directed technologies rather than “general purpose” technologies.

If the rich country's production advantage in good 2 is strong enough, its welfare gain from improving the poor country's technology for good 1 is increasing in the degree of inferiority of that good.

In summary, the rich country benefits most from an improvement in the poor country's technology for the good in which it does not have a comparative advantage, which is produced in large quantities in the poor country, whose technological development cannot spill over to other goods (is directed), and which is inferior. Given these incentives the rich region has for improving the poor region's technology, we focus on a production structure in which the poor country produces only the inferior good. The rich country can produce this good as well as a luxury good. We study the effects of an improvement in the poor country's technology.

The poor region's total production of good 1, Y_{P}, is given by

$$Y_{\mathrm{P}} = A_{\mathrm{P}} L_{\mathrm{P}},$$

where L_{P} is the total labor force of this country and A_{P} is a productivity measure.[10]

The rich country produces both goods. Its production of good 1 is given by

$$Y_{\mathrm{R}}^1 = A_{\mathrm{R}}^1 L_{\mathrm{R}}^1,$$

where $A_{\mathrm{R}}^1 \geqslant A_{\mathrm{P}}$, and with L_{R}^1 denoting the amount of labor used in the production of good 1.[11] Production of the luxury good, labeled 2, requires both capital and labor and is given by

$$Y_{\mathrm{R}}^2 = A_{\mathrm{R}}^2 K_{\mathrm{R}}^{\beta} \left(L_{\mathrm{R}} - L_{\mathrm{R}}^1\right)^{1-\beta},$$

where $A_{\mathrm{R}}^2 > 0$ is the efficiency parameter for sector 2, L_{R} the total labor force, and K_{R} the stock of physical capital of the rich country.[12] Naturally, $L_{\mathrm{R}} \geqslant L_{\mathrm{R}}^1$. Sector 1 can be thought of as representing agriculture, and sector 2, manufacturing ("nonagricultural" in general). Capital evolves according to $\dot{K}_{\mathrm{R}} = i_{\mathrm{R}} - \delta K_{\mathrm{R}}$, where i_{R} denotes gross investment by the rich country. The developed region decides how to allocate its labor between the two sectors and how much to invest in physical capital. We make the realistic assumption that the manufacturing good alone is used for accumulating capital.

The poor country's efficiency parameter, A_{P}, is of fundamental importance for our analysis. We also wish to compare the benefits from increasing A_{P} to those associated with increasing A_{R}^1. Therefore, we will solve for and highlight the dependence of the main variables (prices, quantities, welfare) on A_{P} and A_{R}^1 as we proceed.[13]

To improve the technology from A_{P} to A'_{P}, a country has to expend resources. We assume that this cost, incurred in terms of good 2, is given by the following convex specification:

$$c(A_{\mathrm{P}}, A'_{\mathrm{P}}) = \begin{cases} \frac{1}{2}\left(A'_{\mathrm{P}} - A_{\mathrm{P}}\right)^2, & \text{if } A'_{\mathrm{P}} \geqslant A_{\mathrm{P}} \\ 0, & \text{if } A'_{\mathrm{P}} < A_{\mathrm{P}}. \end{cases} \quad \mathbf{(1)}$$

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

In this section, the analysis is confined to steady-state comparisons; transitions are analyzed in Section 4. Steady-state expressions for income and factor allocations are used to evaluate benefits from improvements. To make the cost compatible with this interpretation, we assume that the investment cost is borne in the steady state in the form of a perpetual payment, $rc(A_{\mathrm{P}}, A'_{\mathrm{P}})$, where r is the interest rate.[14]

If p denotes the relative price of good 2 in units of good 1, the problem of the poor country is

$$\max_{c_{\mathrm{P}}^1, c_{\mathrm{P}}^2, A'_{\mathrm{P}}} \int_0^\infty e^{-\rho t}\left[\theta \log\left(c_{\mathrm{P}}^1 - m_{\mathrm{P}}\right) + (1-\theta)\log c_{\mathrm{P}}^2\right] dt,$$

subject to the constraint

$$c_{\mathrm{P}}^1 + p\left[c_{\mathrm{P}}^2 + rc(A_{\mathrm{P}}, A'_{\mathrm{P}})\right] \leq A_{\mathrm{P}} L_{\mathrm{P}}.$$

The problem of the rich country is

$$\max_{c_{\mathrm{R}}^1, c_{\mathrm{R}}^2, i_{\mathrm{R}}, L_{\mathrm{R}}^1, A'_{\mathrm{P}}} \int_0^\infty e^{-\rho t}\left[\theta \ln\left(c_{\mathrm{R}}^1 - m_{\mathrm{R}}\right) + (1-\theta)\ln c_{\mathrm{R}}^2\right] dt,$$

subject to the constraints

$$c_{\mathrm{R}}^1 + p\left[c_{\mathrm{R}}^2 + i_{\mathrm{R}} + rc(A_{\mathrm{P}}, A'_{\mathrm{P}})\right] \leqslant A_{\mathrm{R}}^1 L_{\mathrm{R}}^1 + pA_{\mathrm{R}}^2 (K_{\mathrm{R}})^\beta \left(L_{\mathrm{R}} - L_{\mathrm{R}}^1\right)^{1-\beta} \quad (2)$$

$$\dot{K}_{\mathrm{R}} = i_{\mathrm{R}} - \delta K_{\mathrm{R}}. \quad (3)$$

There are four crucial ingredients in our analysis: the terms-of-trade effect, the relative sizes of the labor forces (which give rise to a scale effect), the minimum consumption requirement, and costs of technology improvement. We start by ignoring these costs; that is, we ignore the rc term and the choice of A'_{P}. The main points of the paper can be made within this simpler structure. Costs are explicitly considered in Section 3. Although we retain the minimum consumption requirements in the following expressions, it is easy to abstract from their effect by setting the m_is to zero.

Because the poor country has no dynamic choices to make, the solution to its optimization problem is trivially given by:

$$c_{\mathrm{P}}^1 = \theta Y_{\mathrm{P}} + (1-\theta) m_{\mathrm{P}} \quad (4)$$

$$c_{\mathrm{P}}^2 = (1-\theta)\frac{Y_{\mathrm{P}} - m_P}{\mathrm{p}}. \quad (5)$$

For the rich country, we form the current value Hamiltonian of the problem, $\mathcal{H}$, and write the first-order conditions as

$$\left[c_{\mathrm{R}}^1\right]: \frac{\theta}{c_{\mathrm{R}}^1 - m_{\mathrm{R}}} = \lambda_1 \quad (6)$$

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

$$\left[c_{\mathrm{R}}^{2}\right]:\frac{1-\theta}{c_{\mathrm{R}}^{2}}=p\lambda_{1}\tag{7}$$

$$[i_{\mathrm{R}}]:\lambda_{1}p=\lambda\tag{8}$$

$$\left[L_{\mathrm{R}}^{1}\right]:A_{\mathrm{R}}^{1}-(1-\beta)\,pA_{\mathrm{R}}^{2}\,(K_{\mathrm{R}})^{\beta}\left(L_{\mathrm{R}}-L_{\mathrm{R}}^{1}\right)^{-\beta}\leq 0 \qquad \left(\text{w.e.i. } L_{\mathrm{R}}^{1}>0\right)\tag{9}$$

$$\left[\dot{\lambda}-\rho\lambda=-\mathcal{H}_{K_{\mathrm{R}}}\right]:\dot{\lambda}-\rho\lambda=-\left[\lambda_{1}\beta pA_{\mathrm{R}}^{2}\,(K_{\mathrm{R}})^{\beta-1}\left(L_{\mathrm{R}}-L_{\mathrm{R}}^{1}\right)^{1-\beta}-\lambda\delta\right],\tag{10}$$

as well as the budget constraint and the law of motion for capital. Here λ_1 and λ are the multipliers on the budget constraint and the law of motion, respectively.

Using (6) and (7) in the budget constraint, we get

$$c_{\mathrm{R}}^{1}=\theta\left[Y_{\mathrm{R}}^{1}+p\left(Y_{\mathrm{R}}^{2}-i_{\mathrm{R}}\right)\right]+(1-\theta)\,m_{\mathrm{R}}\tag{11}$$

$$c_{\mathrm{R}}^{2}=(1-\theta)\,\frac{\left(Y_{\mathrm{R}}^{1}+p\left(Y_{\mathrm{R}}^{2}-i_{\mathrm{R}}\right)-m_{\mathrm{R}}\right)}{p}.\tag{12}$$

If condition (9) holds with equality, both goods are produced by the rich country. This equality implies a sectoral capital-to-labor ratio of

$$\frac{K_{\mathrm{R}}}{L_{\mathrm{R}}-L_{\mathrm{R}}^{1}}=\left[\frac{1}{(1-\beta)\,p}\frac{A_{\mathrm{R}}^{1}}{A_{\mathrm{R}}^{2}}\right]^{1/\beta}.\tag{13}$$

However, if (9) is a strict inequality even when $L_{\mathrm{R}}^{1}=0$, the rich country specializes in good 2, and good 1 is produced only by the poor country.

2.1. Equilibrium

An equilibrium is simply defined as both regions optimizing according to the problems given above, and the following market clearing condition being satisfied:

$$c_{\mathrm{P}}^{1}+c_{\mathrm{R}}^{1}=Y_{\mathrm{P}}+Y_{\mathrm{R}}^{1}.$$

Using the first-order conditions for consumption in the two regions in the above equilibrium condition, we can get the following alternate equilibrium condition, which we find more useful:[15]

$$\theta p\left(Y_{\mathrm{R}}^{2}-i_{\mathrm{R}}\right)=(1-\theta)\left[Y_{\mathrm{P}}+Y_{\mathrm{R}}^{1}-(m_{\mathrm{P}}+m_{\mathrm{R}})\right].\tag{14}$$

The value of the world consumption of good 2 is equated to the value of total consumption of good 1 in excess of the minimum requirements, up to a factor of the utility weights.

As we show below, the rich country will find itself in one of two steady state regimes: specialized in the production of good 2 or producing both goods. It is

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

straightforward to show that the condition for the nonspecialized steady state to obtain is

$$\left(\frac{\theta}{1-\theta}\right)\left[\frac{\rho+\delta(1-\beta)}{(\rho+\delta)(1-\beta)}\right]A_{\mathrm{R}}^{1}L_{\mathrm{R}} > A_{\mathrm{P}}L_{\mathrm{P}} - (m_{\mathrm{P}}+m_{\mathrm{R}})\,. \qquad \mathbf{(15)}$$

This assumption is more likely to be satisfied when the rich country is capable of producing larger quantities of good 1 than the poor country; in particular, when A_{R}^{1} is large enough relative to A_{P}, L_{R} is not too small relative to L_{P}, the ms are sufficiently large, θ is large enough to make the world consumption needs of good 1 large, and β is high enough to make capital, rather than labor, more important for the production of good 2. The presence of the ms makes it more likely for the condition to be satisfied.

We find the dichotomy of steady states useful in illustrating the effects of an increase in the poor country's technology on the rich country's GNP. In the specialization regime, the rich country benefits in the steady state only by an improvement in the terms-of-trade; there is no factor reallocation effect. In the nonspecialization regime, the rich country benefits only by reallocating labor toward the good in which it has a comparative advantage, the luxury good; there is no improvement in its terms-of-trade. The real world would correspond to a convex combination of the two scenarios in our model; as we will see, this is especially true when the transition is considered.

2.2. Steady State: Specialization

The case of specialization allows us to highlight the terms-of-trade effect. The following claim anchors the analysis in this case. For notational simplicity, we omit the asterisk notation commonly used for steady state quantities; however, it is to be understood that all quantities are evaluated at the steady state.

Claim 1. *When* (15) *fails to hold, the rich country specializes in good 2. An increase in the technology of the poor country,* A_{P}*,*

(1) *Leaves the rich country's steady state capital stock and its production of good 2 unchanged. However, its steady state terms-of-trade improve and increase its income. The improvement in the terms-of-trade is magnified by the inferiority of good 1.*
(2) *Increases the output and the welfare of the poor country if its output is large relative to the minimum consumption levels.*
(3) *Increases the steady state welfare of the rich country because the terms-of-trade move in its favor; this welfare effect is magnified by the degree of inferiority of good 1.*

(**1**) Imposing the steady-state conditions $\dot{\lambda} = \dot{K}_{\mathrm{R}} = 0$, rearranging (10), and setting $L_{\mathrm{R}}^{1} = 0$, we get

$$K_{\mathrm{R}} = L_{\mathrm{R}}\left(\frac{\beta A_{\mathrm{R}}^{2}}{\rho+\delta}\right)^{\frac{1}{1-\beta}}. \qquad \mathbf{(16)}$$

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

The steady state capital stock does not depend on A_{P}. If the rich region is specialized for a given A_{P}, we can see from (15) that it will continue to be specialized for higher A_{P}s; therefore, increases in A_{P} do not affect output in the rich region. Total steady state output of good 2 net of depreciation, $\bar{Y}_{\mathrm{R}}$, is also independent of the poor country's technology.

The trade-balance condition simplifies to $c_{\mathrm{R}}^1 = pc_{\mathrm{P}}^2$. With (5) and (11), this implies that

$$p = \frac{1-\theta}{\theta}\frac{A_{\mathrm{P}}L_{\mathrm{P}} - m_{\mathrm{P}} - m_{\mathrm{R}}}{\bar{Y}_{\mathrm{R}}}. \quad \textbf{(17)}$$

The steady state price increases with A_{P}, because the world output of good 1 increases, with no increase in good 2. The rich country's income, $I_{\mathrm{R}} = p\bar{Y}_{\mathrm{R}}$, also increases.

The elasticity of the rich country's terms-of-trade with respect to A_{P} is

$$\frac{d \ln p}{d \ln A_{\mathrm{P}}} = \frac{A_{\mathrm{P}}L_{\mathrm{P}}}{A_{\mathrm{P}}L_{\mathrm{P}} - m_{\mathrm{P}} - m_{\mathrm{R}}}. \quad \textbf{(18)}$$

This elasticity equals one when the minimum consumption levels are zero and increases when they increase. The inferiority of good 1 thus provides an amplification of the terms-of-trade effect and the incentive the rich region has to improve A_{P}.

(**2**) From (4) we can see that the poor country's consumption of good 1 depends positively on A_{P}. Using the expression for the price, (17), in (5) we get the consumption for the second good as

$$c_{\mathrm{P}}^2 = \theta\frac{A_{\mathrm{P}}L_{\mathrm{P}} - m_{\mathrm{P}}}{A_{\mathrm{P}}L_{\mathrm{P}} - m_{\mathrm{P}} - m_{\mathrm{R}}}\bar{Y}_{\mathrm{R}}.$$

Therefore, c_{P}^2 is a decreasing function of A_{P} for nonzero minimum consumptions. When the ms are zero, c_{P}^2 is independent of A_{P}, and given that c_{P}^1 increases with A_{P}, the poor country's welfare increases unambiguously with technology improvements. The only way to evaluate the general case is to derive the indirect utility function, which for country i in the steady state (ignoring constants) is

$$V_i = \frac{\ln(I_i - m_i) - (1-\theta)\ln p}{\rho}, \quad \textbf{(19)}$$

where the incomes (net of depreciation) are given by

$$I_{\mathrm{P}} \equiv Y_{\mathrm{P}} \text{ and } I_{\mathrm{R}} \equiv Y_{\mathrm{R}}^1 + p\left(Y_{\mathrm{R}}^2 - \delta K_{\mathrm{R}}\right).$$

Using the expressions for price and output, this becomes

$$V_{\mathrm{P}}(A_{\mathrm{P}}) = \frac{1}{\rho}[\ln(I_{\mathrm{P}} - m_{\mathrm{P}}) - (1-\theta)\ln(I_{\mathrm{P}} - m_{\mathrm{P}} - m_{\mathrm{R}}) + (1-\theta)\ln\bar{Y}_{\mathrm{R}}]. \quad \textbf{(20)}$$

It can be seen that, if $A_P L_P > m_P + m_R/\theta$, then $\partial V_P/\partial A_P > 0$; this ensures that the income effect for the poor country due to an increase in A_P is stronger than the terms-of-trade effect. If this condition does not hold, a donation of technology can be "immiserizing" for the poor country.[16]

(**3**) For the rich country, because p increases with A_P, equations (11) and (12) unambiguously show that both c_R^1 and c_R^2 increase with A_P. Evaluating (19), we get the rich country's welfare as

$$V_R(A_P) = \frac{1}{\rho}\{(1-\theta)\ln \bar{Y}_R + \ln[(1-\theta)(I_P - m_P) - m_R] - (1-\theta)\ln(I_P - m_P - m_R)\}. \quad (\mathbf{21})$$

For the rich country, it is always the case that $\partial V_R/\partial A_P \geq 0$ and the inequality is strict whenever $m_R > 0$. The terms-of-trade move in favor of the rich country, and its welfare effect can never be negative.

In (22), I_P is the only determinant of V_R that changes with A_P. Setting $m_R = m_P = m$, we can show that $\partial^2 V_R/(\partial I_P \partial m) > 0$; therefore, the welfare effect of an increase in A_P is magnified by the inferiority of good 1. This is to be expected, as we saw above that the elasticity of the terms-of-trade with respect to A_P increases with m. This elasticity decreases with L_P, which points to the disincentive the rich country might have for raising it.[17]

Even though the consumption of good 2 by the poor country, c_P^2, decreases with A_P, its *value*, pc_P^2, increases; the percentage increase of expenditure on good 2 is higher than on good 1. Therefore, the global market for the good produced by the rich countries increases, in value if not in actual units of goods.

2.3. Steady State: Nonspecialization

We state the following claim for the steady state in which the rich region produces both goods.

Claim 2. *When (15) holds, the rich country produces both goods. An increase in the technology of the poor country,* A_P*,*

(1) *Has no effect on the steady state terms-of-trade.*
(2) *Increases the rich country's capital stock, its production of good 2, its income, and its welfare in the steady state. These effects are magnified by the size of the poor country's labor force and, in the case of welfare, by the degree of inferiority of good 1.*
(3) *Increases the output and the welfare of the poor country.*
(4) *Is preferred by the rich country to an increase in its own technology for the corresponding good if the labor force in the poor country is large enough.*

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

(**1**) The analogue of (16) in this case is

$$\frac{K_R}{L_R - L_R^1} = \left(\frac{\beta A_R^2}{\rho+\delta}\right)^{\frac{1}{1-\beta}}. \tag{22}$$

The capital-to-labor ratio in sector 2 is determined by the developed world's technological and preference parameters alone. At the steady state, $i_R = \delta K_R$, as usual.

Combining (22) with (13), we get[18]

$$p = \frac{A_R^1}{(1-\beta)\left(\frac{\beta}{\rho+\delta}\right)^{\frac{\beta}{1-\beta}} \left(A_R^2\right)^{\frac{1}{1-\beta}}}. \tag{23}$$

Given (22) and (13), the long-run terms-of-trade are also determined solely by the parameters of the rich country and unaffected by any change in A_P.

(**2**) Although there is no terms-of-trade effect, there is a factor-reallocation effect. Using (14) and (23), we derive the equilibrium choice of L_R^1 as

$$L_R^1 = aL_R - b\frac{A_P L_P - (m_P + m_R)}{A_R^1}, \tag{24}$$

where a and b are positive constants. The rich country's employment in sector 1 depends negatively on the poor country's technology, A_P, as well as on its labor force, L_P. Calculating $\partial L_R^1/\partial A_P$, we can see that the negative impact of A_P on the labor force devoted to agriculture in the rich countries is magnified by the *size* of the poor country's labor force. This is a scale effect of technology; the larger the labor force of the poor region working with the technology, the greater the effect of improving it. From (22), one can see that an increase in the steady state labor also increases the capital stock; an increase in the rich country's production of good 2 results.

Since the relative price p does not change, the impact of A_P on consumption and on welfare, as given by (19), is confined to its impact on income, I_j. For the rich country, higher A_P decreases output in sector 1 but increases it in sector 2. Some algebra shows that $I_R = cA_R^1 L_R + e(A_P L_P - (m_P + m_R))$, where c and e are positive constants. Therefore, A_P has a positive effect on the rich country's income net of depreciation. As with L_R^1, the impact of A_P on I_R is magnified by the size of the poor country's labor force.

The improved efficiency of the poor country allows it to produce more of good 1. This enables the rich country to redirect its labor to the capital-intensive sector 2, where it has a comparative advantage. This increases the marginal product of capital, and causes a long run increase in the accumulated capital. Output in sector 1 falls, but the increase in output in sector 2 is enough to increase the income and welfare of the rich country.

Setting $m_R = m_P = m$, we can show that $\partial^2 V_R/(\partial A_P \partial m) > 0$; the welfare effect for the rich country of an increase in A_P is magnified by the inferiority of good 1. The effect on steady state welfare is driven only by the GNP net of the minimum consumption. The higher this minimum, the greater is the percentage effect of labor reallocation toward the rich country's production of the luxury good. The increase in I_R outweighs the direct negative effect of m on the rich country's welfare.

(**3**) The positive relationship between I_P and A_P implies that the poor country's consumption of both goods will also vary positively with A_P. Therefore, both regions unambiguously benefit from a more efficient sector 1 in the developing world.[19]

Though the steady state consumption of both goods increases for the poor country, it increases by a higher percentage for good 2, given that it is a luxury good. The claim often made in policy discourse that improving the condition of the poor countries can only expand the global market for the goods produced by the rich countries is validated in this case too.

(**4**) What are the implications of an improvement in the rich country's own efficiency of sector 1 (higher A_R^1)? From (24), we see that L_R^1 depends positively on A_R^1. This implies that the rich country's output in sector 1 will increase with A_R^1; output in sector 2 decreases, however, both through the reduction in labor and through a lower capital stock (see (22)). There will also be a terms-of-trade effect: $\partial p/\partial A_R^1 > 0$. From the expression given earlier, we can see that the steady state income, I_R, will increase.

The increase in I_R exerts a positive effect on welfare, while the increase in p exerts a negative one. Unlike an increase in A_P, here the rich country shifts resources toward a sector of comparative disadvantage and does not benefit from the increased terms-of-trade. The decreased incentive to accumulate capital and the ensuing decrease in the production of good 2 intensify the negative effect from an increase in p, increasing the likelihood that the rich country would actually prefer an improvement to an inappropriate technology instead of its own. A sufficient condition for this to happen is that

$$\frac{L_P}{L_R} > \underbrace{\frac{\rho + \delta(1-\beta)}{\beta\rho(1-\theta)}}_{>1}. \tag{25}$$

This is another manifestation of the scale effect of technology; the rich country prefers an improvement in the technology exploited by the larger labor force. The welfare of the poor country unambiguously decreases, because the rich country has become more competitive in the poor country's export industry.

3. COSTLY IMPROVEMENTS

We now incorporate the cost of improving A_P. We expect to answer questions of the following nature with this analysis:

(1) Suppose that an invention (idea) for improving A_P arrives exogenously—for example, an academic paper on a high-yield seed variety suitable to the tropics. Given costly adoption, how much is each country willing to invest in the invention to create a

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

usable technology out of it—that is, developing a seed or a malarial drug based on the idea?

(2) Suppose an idea for improving *both* A_P and A_R^1 arrives exogenously. Given costly adoption, are there any conditions under which the rich country chooses to invest in A_P instead of A_R^1? In other words, is the earlier conclusion about the rich country's preference for inappropriate technology robust to the inclusion of costs?

3.1. Specialization

In this section, we substantiate the following claim:[20]

Claim 3. *In the specialized regime:*

Given identical cost functions, the rich country will invest more in improving the poor country's technology than the poor country would do on its own (provided θ is small enough).

We differentiate the expressions for $V_R(A_P)$ and $V_P(A_P)$ in order to get the first-order conditions governing the technology investment of the rich and the poor regions. The condition for the rich region is

$$\frac{\partial p}{\partial A_P} c_P^2 = pr \frac{\partial c\left(A_P', A_P\right)}{\partial A_P}.$$

The net benefit to the rich is the added revenue from exports due to improved terms-of-trade.

Optimal investment for the poor region is given by

$$\frac{\partial Y_P}{\partial A_P} - \frac{\partial p}{\partial A_P}\left[c_P^2 + rc\left(A_P', A_P\right)\right] = pr \frac{\partial c\left(A_P', A_P\right)}{\partial A_P}.$$

The positive impact of increased output net of the added cost of imports is equated to the marginal cost. The inequality $\theta < 0.5$ is sufficient to ensure that the investment by the rich exceeds that by the poor.[21] The rich country benefits from the improvement in the terms-of-trade, whereas the poor country is hurt by it.[22]

3.2. Nonspecialization

We prove the following claim:

Claim 4. *In the nonspecialized regime:*

(1) *Given identical cost functions, the poor country will invest more in improving its own technology than the rich country.*

(2) *If the labor force of the poor country is large enough, the rich country would prefer to improve the poor country's technology (the **in**appropriate one) rather than its own (the appropriate one).*

(**1**) Recall that an increase in A_{P} has no effect on the terms-of-trade, p, but increases I_{R} nevertheless. Therefore, the optimal investment condition will equate the marginal increment in income to the marginal cost of research:

$$\frac{1}{p}\frac{\partial I_{\mathrm{R}}}{\partial A_{\mathrm{P}}} = \frac{1}{p}\frac{\partial Y_{\mathrm{R}}^{1}}{\partial A_{\mathrm{P}}} + \frac{\partial Y_{\mathrm{R}}^{2}}{\partial A_{\mathrm{P}}} = r\frac{\partial c\left(A_{\mathrm{P}}', A_{\mathrm{P}}\right)}{\partial A_{\mathrm{P}}}. \qquad (\mathbf{26})$$

Because I_{R} is strictly increasing in A_{P} and the marginal cost of zero investment is zero, it follows from the above first-order condition that the rich country will always undertake positive investment in A_{P}.

A similar investment rule emerges for the poor country:

$$\frac{1}{p}\frac{\partial I_{\mathrm{P}}}{\partial A_{\mathrm{P}}} = \frac{1}{p}\frac{\partial Y_{\mathrm{P}}}{\partial A_{\mathrm{P}}} = r\frac{\partial c\left(A_{\mathrm{P}}', A_{\mathrm{P}}\right)}{\partial A_{\mathrm{P}}}. \qquad (\mathbf{27})$$

Therefore, *if* the poor country could afford to pay the research cost $rc\,(A_{\mathrm{P}}', A_{\mathrm{P}})$, it would also undertake strictly positive investment in A_{P}.

One can evaluate the marginal benefits in (26) and (27) and show that under the plausible conditions $\delta > \rho$ and $\beta < 2/3$, the poor would invest a greater amount than the rich; the effect on the income of the poor is more direct, through improved technology, whereas the effect on the rich is indirect, through labor reallocation.[23]

(**2**) If the rich country could improve its own domestic agricultural sector, say by incurring the same quadratic cost function as above, could it be the case that it would still prefer to improve A_{P} rather than A_{R}^{1}? In the Appendix (Section A), we show that this is indeed possible if L_{P} is sufficiently large. This shows that our result in Section 2.3 is robust to the inclusion of costs of improvement. The endogenous response of technology improvement to the poor country's labor force (the scale effect) makes it possible that the rich country would choose to improve the poor country's technology rather than its own.

4. DYNAMICS

The steady state comparison of the two regimes reveals stark contrasts. With specialization, there is only a terms-of-trade effect, and the rich country desires an improvement in A_{P} more. Without specialization, there is only a factor reallocation effect, and it is the poor country that desires its technology improvement more. Is the contrast as stark also during transition? To answer this question, to get an insight into the mechanics of the model, and to set the stage for a more realistic quantitative assessment, we study the transitional dynamics in this section. For simplicity, we revert to the case of negligible innovation cost studied in Section 2.

4.1. Specialization

We present the differential equations that characterize the dynamic system in terms of K_{R} and p in Appendix A. When the rich country is specialized initially,

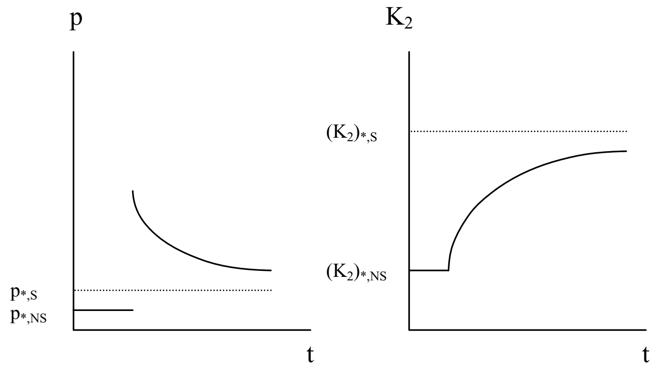

FIGURE 1. Dynamics with specialization: After an increase in A_P; nonspl.→spl.

any increase in A_P will only reinforce specialization [see (15)]. There will be no change in the rich country's steady state capital; the steady state price will increase due to an increase in the production of good 1. The adjustment is instantaneous; therefore, dynamic considerations do not alter the steady state comparisons made earlier.

When the rich country is nonspecialized initially, the dynamics are more interesting. In Appendix A.3, we provide phase diagrams for both these cases, show that the transition paths for the relative price and capital stock when the rich region is initially nonspecialized are as shown in Figure 1, and prove the following claim.

Claim 5. *A sudden increase in A_P*

When the rich country is already in a specialized regime causes the price, p, to increase immediately to its new steady state value. There is no change in the steady state stock of capital.

When the rich country is initially nonspecialized, and the increase causes it to become specialized, causes the stock of capital to increase toward its new steady state value monotonically. The price overshoots its final steady state value at the moment of the increase in A_P and decreases to it over time.

An increase in A_P causes the output of good 1 to increase relative to that of good 2; given the initially fixed nature of the capital stock, p increases. As the capital stock increases, thereby increasing the output of good 2, this price decreases over time, but to a level higher than the initial price. In summary, even when the transition is included, there is always a terms-of-trade effect in favor of the rich country.

4.2. Nonspecialization

We present the dynamic equations in terms of the capital stock K_R, a state variable, and $L_R^2 \equiv L_R - L_R^1$, a jumping variable, in Appendix A.[24] We can back out the

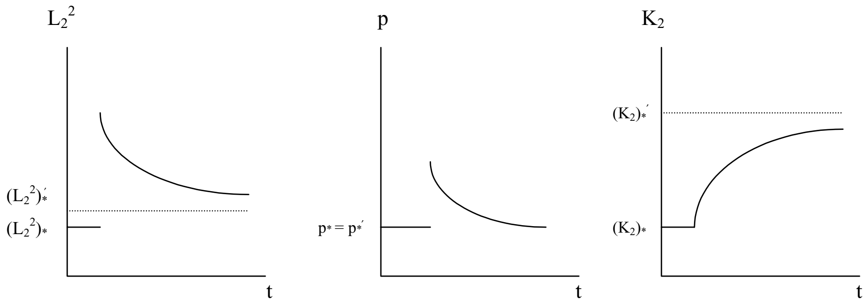

FIGURE 2. Dynamics without specialization: Transition paths after an increase in A_{P}.

price p in terms of these two variables using

$$p = \frac{A_{\mathrm{R}}^{1}}{(1-\beta)A_{\mathrm{R}}^{2}} \left(\frac{L_{\mathrm{R}}^{2}}{K_{\mathrm{R}}}\right)^{\beta}. \tag{28}$$

In particular, note that, for a given K_{R}, p increases with L_{R}^{2}, which will happen at the instant A_{P} is increased.

In Appendix A, we use phase diagrams to argue that the transition paths for the labor allocation to good 1, the relative price, and the capital stock are as shown in Figure 2, and prove the following claim.

Claim 6. *A sudden increase in* A_{P}, *which still obeys the nonspecialization condition,*

Causes the relative price, p, *and the labor devoted by the rich country to good 2,* L_{R}^{2}, *to jump to higher levels at the moment of the increase in* A_{P}.

Over transition, steadily decreases this price to the old steady state value; the labor allocated to good 2 decreases to its new, higher steady state value.

Increases capital monotonically from its old steady state value to its new, higher steady state value.

In the very short run, K_{R} is fixed; any increase in rich-country labor allocated toward good 2 is not enough to counteract the increase in the poor-country supply of good 1 due to the increase in A_{P}. The output of good 1 increases relative to that of good 2, and the relative price, p, jumps.[25] But K_{R}, and thus the supply of good 2, increase over time, which brings the price back to its previous level. Therefore, when the transition to the new steady state is included, there is a terms-of-trade effect as seen in the steady state consideration of the specialization regime; it is in this sense that the inclusion of dynamics makes the dichotomy between the nonspecialized and specialized steady states less stark.

As will be seen in Section 5, the effect on the welfare of both countries due to an increase in A_{P} is smaller when transition is considered. The transitional behavior of the terms-of-trade is one reason for this. The increase in terms-of-trade

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

obviously exerts a negative effect on the poor country, which produces only good 1. Although the rich country does produce the good whose price has increased, the above-mentioned inertia in the production of good 2 causes the positive production effect to kick in slowly, whereas the negative price effect is immediate.

5. THE GREEN REVOLUTION: A QUANTITATIVE ILLUSTRATION

In this section, we examine the historical episode of the Green Revolution (GR) in light of our model. The GR closely resembles the experiments we describe in Section 3: rich countries undertook research to improve agricultural technology specific to poor countries. We view the outcome of this research as a positive change in the technological coefficient, $A_{\rm P}$, of the developing world. We choose empirically plausible values for the parameters of our model and simulate it numerically. We assess the welfare benefits of GR, including transition, by comparing them with the counterfactual situation of no GR. We begin by ignoring the costs of technology improvements for this exercise, which, as mentioned in the Introduction, are not very high. We consider the inclusion of costs later.

We choose $\rho = 0.07$, $\delta = 0.09$, and $\beta = 0.35$ (capital share in rich countries), values typically used in calibrating dynamic models. We set $m_{\rm P} = m_{\rm R} = 0.5$ and $\theta = 0.1$, which jointly yield a minimum consumption value close to 90% of the poor region's consumption of good 1 in the pre-GR period. We later study the dependence of the results on m and θ.[26] We normalize $L_{\rm P} = 1$. Based on the ratio of the population in high-income countries to that in the rest of the world in 1980 (the midpoint of the 1961–2000 period we consider), we set $L_{\rm R} = 0.217$.

We next turn to calibrating the productivity parameters for the two countries. For the poor country's agricultural productivity, we need values for both the counterfactual productivity that assumes no GR ($A_{\rm P}$) and the improved one under GR ($A'_{\rm P}$). For the rich, we need values for productivity parameters in both sectors ($A^1_{\rm R}$ and $A^2_{\rm R}$). The rich country's parameters are calibrated under the assumption of GR, as explained below, and held at those values when the counterfactual experiment with no GR is conducted.

We normalize the counterfactual $A_{\rm P} = 1$. We examine some important historical facts concerning the GR in order to choose the range of values for the food technology index following the Green Revolution. Contrary to common belief, the impact of the GR was felt not just in a small group of countries and only a handful of crops. Evenson and Gollin (2001) extensively examine and document the progress of the GR. Their evidence indicates that many developing countries experienced increased productivity and yields in a variety of food crops. In detailed country studies, they document yield increases not just for crops such as rice and wheat—typically associated with the GR—but also for barley, beans, cassava, groundnuts, lentils, maize, pearl millet, and sorghum. They claim, "Technological advances have occurred in all crops, on all continents, and in all ecological zones, although these advances have been uneven." In addition to the extensiveness of the GR, they also comment on the long-run, highly successful nature of the revolution:

TABLE 1. Yield growth rates, 1961–2000

Crop	γ_P Developing countries: 40-year growth rate (%)	γ_R Developed countries: 40-year growth rate (%)	$(1+\gamma_P)/(1+\gamma_R)$ Gross growth rate factor: developing/developed
Rice (paddy)	117.7	34.6	1.62
Wheat	248.0	116.0	1.61

The GR "is better understood as a 40-year history of steady productivity gains than as a one-time event. [...] Had international research on crop genetic improvement been halted in (say) 1980, the world would be demonstrably worse off."

How can we map the progress of the GR to a one-time change in A_P? In our simple framework, in addition to technological improvements (better seeds), this parameter captures more intensive use of fertilizer and irrigation—which went hand in hand with the adoption of new seeds—and other unmodeled improvements to total factor productivity. Yield increases between 1961 and 2000 would most closely capture the effect of better seeds and increases in complementary inputs.

The UN's Food and Agricultural Organization (FAO) has data on yield growth rates averaged over developing and developed countries.[27] These data reveal the notable impact of the GR in yield improvements. For wheat, the crop with the highest yield increase in the developing world, the 2000 yield was more than three times higher than the 1960 yield, a *growth rate* of 248% for this period.[28] Maize came second, with 153.2%, whereas the yield of all cereals increased by 147.4%. With the exception of barley and lentils, the yield growth experienced in the developing world exceeded that of the developed countries.

Because we hold the rich country's agricultural productivity factor constant and increase only the poor country's productivity, the figure of interest is the gross growth of the developing countries *relative* to that of developed countries. That is, given the growth rates of the rich and the poor, γ_R and γ_P, we are interested is the gross 40-year growth rate factor $(1+\gamma_P)/(1+\gamma_R)$. The factors for rice and wheat are presented in Table 1.

Even though the relative gain for developing countries was less noticeable in other crops, rice deserves disproportionate attention given its enormous impact on calorie intake. Evenson and Gollin (2001) note: "In a number of countries of Asia, rice accounts for more than half of all human food energy—and in the poorest countries, such as Bangladesh, Myanmar, Cambodia, Laos, Vietnam, and eastern India, it contributes over two thirds of the human energy intake." We therefore consider 1.6 as our benchmark estimate of A'_P.[29]

The ratio of TFP between the first quartile and the third quartile countries in 1985 in Hall and Jones (1999) is 3. Given $A'_P = 1.6$, we set the rich country's productivity parameters, $A^1_R = A^2_R$, such that the relative TFP between the rich and

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

TABLE 2. Simulation outcomes

Experiment	↓ in food price	Gain: poor		Gain: rich	
		SS	Tran.	SS	Tran.
$A_P^{'} = 1.30A_P$ (nspl→nspl)	0%	30.0%	29.2%	1.9%	0.07%
$A_P^{'} = 1.60A_P$ (nspl→ spl)	36.5%	23.1%	21.4%	12.1%	9.9%
$A_P^{'} = 1.76A_P$ (nspl→spl)	50.0%	17.6%	16.1%	16.6%	14.3%

poor countries, in 1985, is in the ballpark of this figure. Setting $A_R^1 = A_R^2 = 8A_P'$ yields a TFP factor of 3.2 in 1985 in the model outcome.[30]

We additionally use output growth, rather than yield growth, to get a lower bound for the increase in A_P. Higher yields should materialize less than one-for-one into food production, as the general equilibrium effect of a lower price would deter farmers from expanding output in the same proportion as productivity improvements. FAO also provide indices for total food production per capita. Whereas the corresponding growth rate is an impressive 62.2% for the developing countries, it is only 23% in the developed world. The relative growth rate factor for food production, calculated analogously to the figures in Table 1, is 1.32. We therefore set 1.3 as our lower bound for A_P'. We leave the rich country's technological parameters the same as those of the benchmark case of $A_P' = 1.6$.

For an empirical target, which we do not explicitly calibrate to but can compare the simulation outcome with to get some validity on the parameter choices, we use the terms-of-trade data—a 50% decrease in food prices reported in Evenson and Gollin (2001).

The rich region is not specialized before the transfer of technology to the poor region. In Table 2, we present the post-Green Revolution outcomes for the above-mentioned values of the final productivity index, A_P'.[31]

In the first ("lower bound") case of $A_P' = 1.3A_P$, the new level of technology in the poor region is not high enough to cause the rich one to specialize. As seen in Section 2, the steady state capital of the rich country, as well the labor it devotes to the production of good 2, increase in response to an increase in A_P, both by 10.8%. The steady state price does not change; as mentioned earlier, the long-run capital-labor ratio and thus the price are pinned down completely by the rich country's parameters. However, the transition price is higher than the steady state price, overshooting by about 4% at the time of the transfer. In the benchmark case of $A_P' = 1.6A_P$, the increase in A_P is high enough to cause the rich country to specialize. The food price declines by 36.5%, which is lower than the 50% drop mentioned above. (The price of food will be the inverse of the price of the manufactured good, p, of the model.) We search for the increase in A_P that would nail the food price drop of 50%. This happens for $A_P' = 1.76A_P$; the outcomes for this case are presented in the last row of Table 2. The steady state capital stock of the rich and the labor it devotes to manufacturing increase by 13.7% in the last two cases.

The welfare gain is shown as an equivalent variation in baseline income, considering only steady states, as well as including the transition, which is "complete" in the 40-year period considered. As A'_P increases, the welfare gain increases for the rich region and decreases for the poor region, even though the poor gain more in percentage terms than the rich in all three cases. In the first case, the gains of the poor outstrip those of the rich by large margins. Indeed, inclusive of transition, the rich country barely gains anything. In the second (benchmark) case, the gains of the poor, 23.1% across steady states, and 21.4% including transition, exceed those of the rich, 12.1% and 9.9%, by smaller amounts. The gap is further narrowed in the last case. For the poor country, the increase in the price of its import good during transition tempers welfare gains. For the rich country, the initial reduction in consumption from increased investment and the slow increase in the production of good 2 temper welfare gains relative to a jump from the old steady state to the new. These figures are consistent with the earlier theoretical results—the large increases in the rich country's terms-of-trade when it is specialized benefit the rich country. The more important finding is that there are realistic parameter values for which both countries benefit from an increase in A_P.

5.1. Discussion of Welfare Gains

The welfare gains, for the poor in the first case, and for the rich in the last case, might seem excessive. The following points have to be borne in mind while interpreting these numbers. The equivalent increase is based on lifetime utility increases; on an annualized basis, these gains would be smaller. Likewise, when population growth, especially in the poor region, is accounted for, the per capita increase in welfare will be lower. For the rich, clearly a move to specialization and the ensuing terms-of-trade effects magnify the welfare effects. In the context of a full-fledged product ladder model, improving A_P might cause both countries to move to more sophisticated goods up the ladder, leading to a more muted terms-of-trade effect.

Table 2 also seems to indicate that the rich country has an incentive to increase the technology as much as possible. However, notice that the welfare gain of the poor is lower with higher A_P. It is not enough that a donation is given; it must also be accepted. The above figures also assume negligible costs, and it would be reasonable to assume that convex improvement costs would mute the welfare effect for the rich. On a different front, there would likely be (unmodeled) political pressure from the labor-intensive sector 1 in the rich country to moving toward specialization in good 2.

Finally, it is natural to ask the following question: If welfare increases via donations are so large for the developed countries, why do we not see many more such donations? Technological transfers seen during the GR are likely unique and hard to replicate. Genetically modified seeds adapted to the climate of one specific region are likely to be of little use in a region with a different climate. This eliminates a number of problems that plague other types of

TABLE 3. Sensitivity analysis

		Gain: poor		Gain: rich	
Experiment: $A'_P = 1.6A_P$ (nspl→spl)	↓ in food price	SS	Tran.	SS	Tran.
Benchmark parameters	36.5%	23.1%	21.4%	12.1%	9.9%
↑ θ alone from 0.1 to 0.125	18.4%	42.1%	39.5%	8.0%	5.5%
↑ m alone from 0.5 to 0.525	30.7%	29.7%	27.6%	10.9%	8.3%

donations. For example, in the case of drugs, one concern drug companies have regarding the donation of low-cost medicine to developing countries is the possibility that corrupt officials might hold on to the drugs and resell them to rich consumers in the developed world. Genetically modified seeds are not prone to such corrupt uses. Therefore, despite the success of the GR, as measured by the welfare numbers in Table 2, similar initiatives on such a scale have rarely been seen.

5.2. Sensitivity Analysis

The parameters m and θ are the least tightly calibrated above. We vary these one at a time, holding all other parameters at the benchmark levels to study the effect on the results reported above. The results of this analysis are presented in Table 3; the benchmark results are presented in the first row for convenience.

When the utility weight for food, θ, is increased from 0.1 to 0.125, the welfare gain for the poor country increases—from 21.4%, including transition, when $\theta = 0.1$, to 39.5% when $\theta = 0.125$—but for the rich country, it drops from 9.9% to 5.5%. It is intuitive that the increase in the utility weight of the good that the poor country produces— food—strengthens its position. The price increase of the manufacturing good (decrease in food price) is muted; see (17). The poor country therefore gains in welfare relative to the rich. If θ increases to the point where (15) fails to hold, say a value such as $\theta = 0.3$, there is no change in the steady state terms-of-trade, and the poor country gains even more in welfare terms. When the minimum consumption values are increased from 0.5 to 0.525, there is a similar muting of food price decrease, and the poor country benefits more from the technology improvement.

There is a change of regime from nonspecialization to specialization in the above examples, which makes it harder to illustrate the claims made in Sections 2.2 and 2.3 directly. Purely to shed further light on the workings of the model and illustrate the claim in Section 2.2, we consider a change of m from 0.1 to 0.2, which starts the rich country with specialization and leaves it specialized when $A'_P = 1.6A_P$. The percentage drop in food price increases as m increases, from 42.9% to 50%; that is, the increase in manufacturing price, p, is higher with increasing inferiority, as claimed. The rich country's welfare gain jumps, from

6.3% to 8.9%, as claimed. To illustrate the claim in Section 2.3, we consider a change of m from 0.65 to 0.85, which starts the rich country with lack of specialization and leaves it nonspecialized when $A'_P = 1.6A_P$. Although there is no change in the terms-of-trade, as claimed, there is a slight increase in the welfare gain of the rich, from 3.8% to 3.9%. Finally, to illustrate the model's scale effect in the case of nonspecialization, for the $m = 0.85$ case mentioned above, we decrease L_R to 0.15 from its benchmark value of 0.217. As argued in the claim in Section 2.3, an increase in the (relative) labor force of the poor country increases the effect of a technology donation. The resource reallocation effect is stronger for the rich country (manufacturing output increases by 49.2% instead of 28.9%), and its welfare gain is greater (5.7% instead of 3.9%).

5.3. Considering Costs

In the quantitative analysis, we have thus far ignored the cost to the rich country of improving the poor country's technology. Is this reasonable? The 1998 budget of the Consultative Group for International Agricultural Research (CGIAR), an institution that consolidated the GR research efforts of the international community, was \$340 million. This is a mere 0.00153% of the GDP of the developed world.[32] How can we compare it with the benefits for the rich as given in Table 2? For the benchmark case, the gains net of transition costs amount to about 10% of base-year income. On an annual basis, this 40-year gain corresponds to a growth rate of 0.24%, far outweighing the above-mentioned cost. Even when the smallest gain reported in Table 2 is used, the gain exceeds the cost.

Another way to put the research costs of the rich in perspective is to use the cost specification (1) of our theoretical analysis, even though this is not a calibrated cost function. The present value of the costs is obtained by multiplying the cost of the manufacturing good, p, by this expression. For the benchmark case of $A'_P = 1.6A_P$, this cost amounts to about 2% of the rich country's pre-GR steady state income. The steady state income gain of 12.1%, given in Table 2, is much higher than this cost. Evidently, the gains for the rich *net* of research costs are still positive.

5.4. Tariffs

The harm caused to the developing countries by the agricultural protectionism of the developed countries has received considerable attention in the literature.[33] Cohen and Sisler (1971) analyze imports by Europe, Japan, the United Kingdom, and the USSR from the LDCs and find that they grew in the 60s; imports of rice from LDCs, a crop particularly relevant to the Green Revolution, grew at a healthy 7.2% a year. They conclude that the world demand for the products exported by developing nations had been much stronger than predicted. Protectionism did not completely choke off LDC exports.

Our argument thus far has been that the rich also benefited from the Green Revolution. Therefore, we need to examine the welfare effects of tariffs on rich countries. If the rich region levies a tariff of rate τ on good 1 (its import good) and $A'_{\mathrm{P}} = 1.6A_{\mathrm{P}}$, how high should this tariff rate be before its steady state welfare gains realized from an increase in A_{P} are negated? If the government repatriates all revenues in a lump-sum fashion to the consumer, a 16% tariff rate is enough to negate the gains for the rich. When the government uses the revenues to purchase goods for its own consumption, the tariff rate has to be three hundred percent to negate the welfare gains for the rich, a high value even for protectionist regimes. Nevertheless, it is clear that the rich countries would realize greater gains if they did not levy tariffs.

6. CONCLUSION

In this paper we have demonstrated, under various assumptions, that rich countries have an economic incentive to improve the technology specific to poor countries. Although altruistic and humanitarian considerations have cornered most public attention, we show there are also economic reasons for the rich countries to become involved in solving problems particular to developing countries. The welfare effects of the Green Revolution, a classic case of such an "intervention," are positive in a model simulated with realistic parameter values. With the various changes both rich and poor countries have undergone in the last 40 years, isolating one episode in a macro context is difficult; we therefore view the positive results as an encouraging sign of the applicability of our model.

As mentioned in the Introduction, we have been silent on the issues of coordination among rich countries that make such a collective endeavor possible in the first place, as well as on the nature of commitment, or lack thereof, by the poor to behave in ways expected by the rich who donate the technology to them. Our representative agent framework also ignores political economy questions. Modeling these features explicitly will allow us to better understand why such collective efforts have not been more widespread and are limited to certain types of technological improvements, most notably agriculture. These are topics of ongoing research.

NOTES

1. For instance, Jeffrey Sachs (1999) makes the plea, "To the extent that the poor face distinctive challenges, science and technology must be directed purposefully towards them," and again notes, "It is very rare, alas, that technologies are developed by the private sector to meet specific challenges in the poor countries (for example, for tropical foods or diseases)" (Sachs 2005, p. 282).
2. Although this assumption can be justified on the basis of empirical relevance, it is also a conservative one. If rich countries have an incentive to provide technologies specific to poor countries for free, they will be even more likely to do so when they are paid for these technologies.
3. The cost outlays for the Green Revolution, an episode we use to illustrate our framework, were quite low, making this an empirically relevant exercise.

4. The real price of food in international markets is less than half its level of 50 years ago. The FAO's index of food production per capita for developing countries increased tremendously, as shown in Table 1. See Evenson and Gollin (2001) for a comprehensive summary.

5. The following quotation from the *Economist*, dated February 22, 2001, is relevant in this regard: "The case for much more generous provision of life-saving drugs to the developing countries is irresistible both morally and as a matter of economics. But it is naive, wrong and in the long run counter-productive, to expect the cost of this aid to be met out of drug-company profits. Instead, rich-world taxpayers should pay. It would be much better to spend aid money on drugs for developing countries than it is to waste it in the usual ways."

6. We realize that patent enforcement does have a positive effect on R&D. Our point here is to show that there are also beneficial effects associated with technological imitation, especially across developed-developing country boundaries. This is related to, but different from, the case against intellectual monopoly made by Boldrin and Levine (2002). Also see Sachs et al. (2001) in this regard.

7. The indexation of m by i allows for the possibility that the norms for a minimum can change with the level of development. Inferiority of food is an empirical reality we cannot ignore. The *2000 World Development Indicators* reports that only 13% of consumption expenditures in the United States in 1998 and 14% in the United Kingdom were for food. This figure is much higher for developing countries—49% in Bangladesh, 47% in Indonesia, and 45% in Pakistan. See Chatterjee and Ravikumar (1999) for an exposition on minimum consumption in a macroeconomic context.

8. Throughout the paper, we interpret the minimum consumption requirements m_i as aggregate requirements proportional to population size. Given this, we use the aggregate agent's utility for analysis instead of multiplying individual utility by the number of agents. This is done for ease of exposition and nothing crucial, including the scale effect highlighted below, depends on this. As will be seen from (25), it is the *ratio* of labor forces between the two regions that matters for the scale effect.

9. Details of this analysis are available from the authors upon request.

10. We have assumed that all poor countries can be lumped into a region and the same technology is appropriate for all. Given that a vast majority of the developing countries are in the arid or semiarid tropics, agricultural and health concerns are likely to be very similar for them.

11. Note that the rich country has an absolute advantage in the production of food. Given the possibility of technology transfer in this sector, absolute advantage matters (whereas in classic trade models comparative advantage alone matters).

12. Our main results should go through when capital is used in both sectors, provided that the technology for good 1 is less capital-intensive than the technology for good 2.

13. We assume that the parameters of the model satisfy the following inequality: $A_{\mathrm{P}}L_{\mathrm{P}} > m_{\mathrm{P}} + [1/(1-2\theta)]m_{\mathrm{R}}$. This assumption guarantees that, if good 1 is only produced by the poor country, the output will be enough to satisfy both countries' aggregate minimal consumption requirements. It also ensures the empirically plausible outcome of the rich country consuming more of good 2 than the poor country.

14. It can be shown that even if the interest rate is driven endogenously by the developed world, an empirically plausible supposition, the results are qualitatively similar.

15. By using the rich region's budget constraint with the market clearing condition for good 1, one can obtain the usual balance of trade condition: $p(Y_{\mathrm{R}}^2 - c_{\mathrm{R}}^2 - i_{\mathrm{R}}) = Y_{\mathrm{P}} - c_{\mathrm{P}}^1$.

16. Also, see Matsuyama (2000) in this regard. How does $\partial V_{\mathrm{P}}/\partial A_{\mathrm{P}}$ depend on the poor country's labor force L_{P}? The higher L_{P} makes the country richer, but also increases the terms-of-trade in favor of the rich. However, it can be shown that $\theta < 1/2$ is sufficient to guarantee $\partial^2 V_{\mathrm{P}}/\partial A_{\mathrm{P}}\partial L_{\mathrm{P}} > 0$.

17. For a more general CES utility specification, if the elasticity of substitution is greater than one, the terms-of-trade effect, including its magnification by the inferiority for good 1, should be more muted. After a technological donation, the poor country's demand for good 2 would increase by less when the elasticity of substitution was higher.

18. We also note that the relative price of good 2 is continuous across the specialization and nonspecialization regimes, as are the steady-state utility functions, V_{P} and V_{R}. However, there is a

discontinuity in the derivatives of V_R and V_P with respect to A_P at the critical value of A_P that triggers specialization.

19. Because there is no steady state change in the terms-of-trade, $\partial^2 V_P/\partial A_P \partial L_P > 0$ obtains here more readily than in the case of specialization.

20. We ignore the implications that the explicit introduction of costly investment has for the equilibrium quantities derived in Sections 2.3 and 2.2. For example, total output of the rich country under nonspecialization, $I_R(A_P)$, would now depend on its expenditure on technology improvement. Since this does not alter the qualitative results below, and the magnitude of this cost is likely to be very small relative to the size of the rich country's GNP, we choose not to consider it explicitly. We also find it analytically convenient to consider welfare changes when the technological change leaves the regime for the rich country—nonspecialized or specialized—unchanged. We study a switch in regime in the sections on dynamics and numerical simulation.

21. The exact condition is $((1-\theta)/\theta)((I_P - m_P)/(I_P - m_P - m_R/\theta)) > 1$.

22. A global planner who maximizes a weighted sum of the welfare of both countries would also invest more than the poor country would. Such a planner is not concerned with redistributive effects of a change in p.

23. A global planner would perceive the *sum* of the benefits perceived by the individual countries. Consequently, the efficient investment in technology improvement exceeds the investment undertaken by either country acting on its own. Such investment would result in a decentralized setting if markets existed for the rich country to sell or license technology improvements in A_P to the poor; such markets have been assumed away in our setup.

24. This choice of the dynamic system variables happens to be convenient. We, of course, cannot use L_R^2 as a variable in the specialization case discussed above.

25. The initial jump in L_R^2 could be high enough to cause the rich region to temporarily specialize in good 2.

26. The model implies that $c_P^1 = \theta I_P + (1-\theta) m_P$, which connects $m = m_P$ and θ, for the assumed value of $m_P/c_P^1 = 0.9$. Our choice of 90% for this ratio was motivated by the following analysis. Under the interpretation that the minimum consumption requirements are subsistence levels, we first used the \$1 a day standard of the 1990 *World Development Report* of the World Bank (measured in 1985 international PPP prices). This would imply a yearly amount of \$365 for subsistence alone, a number which the data suggested was significantly above the annual per capita food consumption of the developing countries. As a consequence, we set the ratio to a high enough value of 90% and study the sensitivity of results to m and θ.

27. FAOSTAT online data was obtained from http://faostat.fao.org.

28. This is in line with estimates of the growth rate of land-augmenting technology performed by Abler et al. (1994) for the "North" region of India, for the period 1960–1987. The North is one of the four areas into which they divide the agricultural sector in India, and the most successful in terms of GR outcomes. Extrapolating the average growth rate for the period 1960–1987 over the 40-year span of 1960–2000 gives a growth rate of 248%. See their Table 6.3.

29. The relative 40-year gross growth rate factors for other crops are 1.23 for potatoes, 1.11 for sorghum, 1.09 for maize, 1.02 for millet, and 1.12 for all cereals.

30. The rich-poor TFP ratio is calculated as $(Y_R^1 + pY_R^2)/[(K_R^\beta L_R^{1-\beta})(A'_P)]$. That is, the total value of output of the rich country is presumed to have arisen from the aggregate Cobb–Douglas production function, $A_R K_R^\beta L_R^{1-\beta}$. We do not use the fourth quartile of countries in the Hall and Jones (1999) productivity list, which are mainly African countries where the Green Revolution did not take root. Calibrating the rich country's technology parameters to a different TFP factor, say 3.75, which is the TFP ratio of the US to India, a "typical" Green Revolution country, will not qualitatively alter the results.

31. The differential equations for the dynamic system were computed using MATLAB's *ode23* routine; the program is available from the authors.

32. This figure is computed by dividing \$340 million by the total 1998 GDP of the high-human-development countries, from the 1998 United Nations *Human Development Report*.

33. See Morisset (1998) for a recent example and the references therein.
34. Detailed derivations are available from the authors on request.

REFERENCES

Abler, David, George Tolley, and G. K. Kripalani (1994) *Technical Change and Income Distribution in Indian Agriculture*. Boulder, CO: Westview Press.

Acemoglu, Daron and Fabrizio Zilibotti (2001) Productivity differences. *Quarterly Journal of Economics* 115, 563–606.

Bhagwati, Jagdish (1958) Immiserizing growth: A geometrical note. *Review of Economics Studies* 25, 201–205.

Basu, Susanto and David N. Weil (1998) Appropriate technology and growth. *Quarterly Journal of Economics* 113, 1025–1054.

Baxter, Marianne (1992) Fiscal policy, specialization, and trade in the two-sector model: The return of Ricardo? *Journal of Political Economy* 100, 713–744.

Boldrin, Michele and David Levine (2002) The case against intellectual property. *American Economic Review* 92, 209–212.

Chatterjee, Satyajit and B. Ravikumar (1999) Minimum consumption requirements: Theoretical and quantitative implications for growth and distribution. *Macroeconomic Dynamics* 3, 482–505.

Cohen, Benjamin I. and Daniel G. Sisler (1971) Exports of developing countries in the 1960's. *Review of Economics and Statistics* 53, 354–361.

Desmet, Klaus (2002) A simple dynamic model of uneven development and overtaking. *Economic Journal* 112, 894–918.

Evenson, R. E. and Douglas Gollin (2001) Crop genetic improvement in developing countries: overview and summary. In R. E. Evenson and D. Gollin (eds.), *Crop Variety Improvement and Its Effect on Productivity: The Impact of International Agricultural Research*, pp. 7–38. Wallingford, UK: CAB International.

Hall, Robert E. and Charles I. Jones (1999) Why do some countries produce so much more output per worker than others? *Quarterly Journal of Economics* 114, 83–116.

Matsuyama, Kiminori (2000) A Ricardian model with a continuum of goods under nonhomothetic preferences: Demand complementarities, income distribution, and North-South trade. *Journal of Political Economy* 108, 1093–1120.

Morisset, Jacques (1998) Unfair trade? The increasing gap between world and domestic prices in commodity markets during the past 25 years. *World Bank Economic Review* 12, 503–526.

Rivera-Batiz, Luis A. and Paul M. Romer (1991) Economic integration and endogenous growth. *Quarterly Journal of Economics* 106, 531–555.

Romer, Paul M. (1990) Endogenous technological change. *Journal of Political Economy* 98, S71–S102.

Sachs, Jeffrey D. (1999) Helping the world's poorest. *The Economist*, August 12, 1999.

Sachs, Jeffrey D. (2005) *The End of Poverty: Economic Possibilities for Our Time*. New York: Penguin.

Sachs, Jeffrey D, Michael Kremer, and Amar Hamoudi (2001) The Case for a Vaccine Purchase Fund. Working Paper, Center for International Development Policy at Harvard University.

APPENDIX

A.1. INAPPROPRIATE VS APPROPRIATE TECHNOLOGY INVESTMENT

When the rich country can simultaneously increase A_P and A_R^1, the costs $rc[A'_P, A_P]$ and $rc[(A_R^1)', A_R^1]$ are on the left-hand side of the budget constraint. The first-order condition

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

for the optimal investment in A_{P} is (26). The corresponding condition for investments in A_{R}^{1} is

$$\frac{\partial Y_{\mathrm{R}}^{1}}{\partial A_{\mathrm{R}}^{1}} + \frac{\partial p}{\partial A_{\mathrm{R}}^{1}} \left\{ \bar{Y}^{2} - c_{\mathrm{R}}^{2} - i_{\mathrm{R}} - rc(A_{\mathrm{P}}', A_{\mathrm{P}}) - rc\left[\left(A_{\mathrm{R}}^{1}\right)', A_{\mathrm{R}}^{1} \right] \right\} + p \frac{\partial Y_{\mathrm{R}}^{2}}{\partial A_{\mathrm{R}}^{1}}$$
$$\leq pr \frac{\partial c\left[\left(A_{\mathrm{R}}^{1}\right)', A_{\mathrm{R}}^{1} \right]}{\partial A_{\mathrm{R}}^{1}}, \tag{A.1}$$

with equality if the investment in A_{R}^{1} is strictly positive.

Given (1), the optimal choice of A_{P}' is

$$A_{\mathrm{P}}' = A_{\mathrm{P}} + \frac{1}{r} \frac{(1-\beta)\left(\dfrac{\beta}{\rho+\delta}\right)^{\frac{\beta}{1-\beta}} \left(A_{\mathrm{R}}^{2}\right)^{\frac{1}{1-\beta}}}{A_{\mathrm{R}}^{1}} \frac{\beta\rho(1-\theta)}{(1-\beta)(\rho+\delta)+\beta\rho\theta} L_{\mathrm{P}}, \tag{A.2}$$

which depends positively on L_{P}, a manifestation of the scale effect. The rich country prefers not to invest in its own technology only if the left-hand side of (A.1) evaluated at $(A_{\mathrm{R}}^{1})' = A_{\mathrm{R}}^{1}$ is negative, because the marginal cost is zero with no improvement. Some tedious algebra shows that the condition for this to happen is

$$\frac{\theta}{1-\beta} \frac{\rho+\delta(1-\beta)}{\rho+\delta} A_{\mathrm{R}}^{1} L_{\mathrm{R}} - (1-\theta) \left\{ \frac{1}{1-\beta} - \left[(1-\theta) + \theta \frac{\rho+\delta(1-\beta)}{(\rho+\delta)(1-\beta)} \right] \right\}$$
$$\times [(Y_{\mathrm{P}})' - m_{\mathrm{P}}] + \frac{1-\theta}{1-\beta} m_{\mathrm{R}} \leq 0,$$

where $(Y_{\mathrm{P}})'$ is the new output of good 1 in the poor country given optimal investment in A_{P}. The $[(Y_{\mathrm{P}})' - m_{\mathrm{P}}]$ term is multiplied by a negative factor. Using (A.2), we get

$$(Y_{\mathrm{P}})' = A_{\mathrm{P}} L_{\mathrm{P}} + \frac{1}{r} \frac{(1-\beta)\left(\dfrac{\beta}{\rho+\delta}\right)^{\frac{\beta}{1-\beta}} \left(A_{\mathrm{R}}^{2}\right)^{\frac{1}{1-\beta}}}{A_{\mathrm{R}}^{1}} \frac{\beta\rho(1-\theta)}{(1-\beta)(\rho+\delta)+\beta\rho\theta} (L_{\mathrm{P}})^{2}.$$

Therefore, there exists a large enough L_{P} to make the FOC hold with inequality in a strict sense; this is particularly so because $(Y_{\mathrm{P}})'$ includes a term in the square of L_{P}.

The rich country's incentive to invest in the poor country's technology, A_{P}, is amplified by the size of its labor force, L_{P}. With a quadratic cost specification, the improvement in A_{P} is linear in L_{P}. Given the production technology, $Y_{\mathrm{P}} = A_{\mathrm{P}} L_{\mathrm{P}}$, the square term in the size of the labor force manifests in the above expression for the improved output. The endogenous response of technology improvement to L_{P} makes it more likely that the rich country would improve the poor country's technology rather than its own, for large enough L_{P}.

A.2. DIFFERENTIAL EQUATIONS FOR SPECIALIZATION

The differential equations are

$$\dot{K}_{\mathrm{R}} = A_{\mathrm{R}}^{2} K_{\mathrm{R}}^{\beta} L_{\mathrm{R}}^{1-\beta} - \left(\frac{1-\theta}{\theta}\right) \left[\frac{A_{\mathrm{P}} L_{\mathrm{P}} - (m_{\mathrm{P}} + m_{\mathrm{R}})}{p} \right] - \delta K_{\mathrm{R}}, \tag{A.3}$$

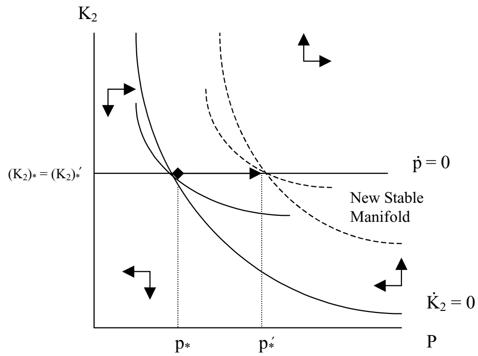

FIGURE A.1. Dynamics with specialization: After A_{P} increase; spl.→ spl.

$$\frac{\dot{p}}{p} = (\rho + \delta) - \beta A_{\mathrm{R}}^2 \left(\frac{L_{\mathrm{R}}}{K_{\mathrm{R}}}\right)^{1-\beta}. \quad \textbf{(A.4)}$$

The steady state quantities are

$$(K_{\mathrm{R}})_{*,\mathrm{S}} = \left(\frac{\beta A_{\mathrm{R}}^2}{\rho + \delta}\right)^{\frac{1}{1-\beta}} L_{\mathrm{R}},$$

$$(I_{\mathrm{R}})_{*,\mathrm{S}} = A_{\mathrm{R}}^2 (K_{\mathrm{R}}^*)^{\beta} L_{\mathrm{R}}^{1-\beta} - \delta K_{\mathrm{R}}^* = \frac{[\rho + \delta(1-\beta)]}{\beta}(K_{\mathrm{R}})_{*,\mathrm{S}},$$

$$(p)_{*,\mathrm{S}} = \left(\frac{1-\theta}{\theta}\right)\left(\frac{I_{\mathrm{P}} - m_{\mathrm{P}} - m_{\mathrm{R}}}{I_{\mathrm{R}}^*}\right).$$

A.3. PROOF OF CLAIM 5

To draw the phase diagram for the system in (A.3) and (A.4), note that the $\dot{K}_{\mathrm{R}} = 0$ locus is given by

$$A_{\mathrm{R}}^2 K_{\mathrm{R}}^{\beta} L_{\mathrm{R}}^{1-\beta} - \delta K_{\mathrm{R}} = \left(\frac{1-\theta}{\theta}\right)\left[\frac{A_{\mathrm{P}} L_{\mathrm{P}} - (m_{\mathrm{P}} + m_{\mathrm{R}})}{p}\right].$$

It is clear that this locus is decreasing in p. The $\dot{p} = 0$ locus is

$$K_{\mathrm{R}} = \left(\frac{\beta A_{\mathrm{R}}^2}{\rho + \delta}\right)^{\frac{1}{1-\beta}} L_{\mathrm{R}} = (K_{\mathrm{R}})_{*,\mathrm{S}},$$

which is independent of p.

When A_{P} increases, the $\dot{K}_{\mathrm{R}} = 0$ locus shifts rightward, while the $\dot{p} = 0$ locus is unchanged. For a change in A_{P} that causes eventual specialization by the rich country, there are two cases to consider—the case where the rich country was specialized to begin with and where it was nonspecialized. Figure A.1 shows the effect on the phase diagram due to an increase in A_{P} when the rich country is specialized initially. The dotted lines show the

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

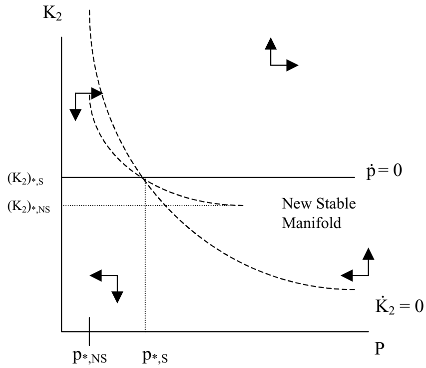

FIGURE A.2. Dynamics with specialization: After A_{P} increase; nonspl.→ spl.

new situation. Any increase in A_{P} will only reinforce specialization; see (15). There is no change in the rich country's steady state capital and the steady state price will increase. The adjustment is instantaneous, along the $\dot{p} = 0$ locus.

When the rich country is nonspecialized initially, the dynamics are more interesting and the new loci (alone) are shown in Figure A.2.

The steady state capital stock for the two regimes is

$$(K_{\mathrm{R}})_{*,\mathrm{NS}} = \left(\frac{\beta A_{\mathrm{R}}^2}{\rho+\delta}\right)^{\frac{1}{1-\beta}} \left(L_{\mathrm{R}}^2\right)_* < \left(\frac{\beta A_{\mathrm{R}}^2}{\rho+\delta}\right)^{\frac{1}{1-\beta}} L_{\mathrm{R}} = (K_{\mathrm{R}})_{*,\mathrm{S}},$$

given that $(L_{\mathrm{R}}^2)_* < L_{\mathrm{R}}$. From (9), for the rich country to be specialized, $A_{\mathrm{R}}^1 < (1-\beta)pA_{\mathrm{R}}^2(K_{\mathrm{R}})^{\beta}(L_{\mathrm{R}})^{-\beta}$, and this implies

$$(p)_{*,\mathrm{S}} > \frac{A_{\mathrm{R}}^1}{(1-\beta)\left(\frac{\beta}{\rho+\delta}\right)^{\frac{\beta}{1-\beta}}\left(A_{\mathrm{R}}^2\right)^{\frac{1}{1-\beta}}} = (p)_{*,\mathrm{NS}}.$$

Therefore, during transition, the capital stock increases monotonically from $(K_{\mathrm{R}})_{*,\mathrm{NS}}$ to $(K_{\mathrm{R}})_{*,\mathrm{S}}$ according to (A.3). The price p overshoots and decreases monotonically to its new, higher steady state level according to (A.4).

A.4. DIFFERENTIAL EQUATIONS FOR NONSPECIALIZATION

The differential equations that characterize the dynamics of the system are[34]

$$\dot{K}_{\mathrm{R}} = \left\{1 + (1-\beta)\left(\frac{1-\theta}{\theta}\right)\right\} A_{\mathrm{R}}^2 K_{\mathrm{R}}^{\beta}\left(L_{\mathrm{R}}^2\right)^{1-\beta} - \delta K_{\mathrm{R}}$$
$$- \left(\frac{1-\theta}{\theta}\right)(1-\beta)\left[A_{\mathrm{P}}L_{\mathrm{P}} - m_{\mathrm{P}} + A_{\mathrm{R}}^1 L_{\mathrm{R}} - m_{\mathrm{R}}\right]\left(\frac{A_{\mathrm{R}}^2}{A_{\mathrm{R}}^1}\right)\left(\frac{K_{\mathrm{R}}}{L_{\mathrm{R}}^2}\right)^{\beta}; \qquad \textbf{(A.5)}$$

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

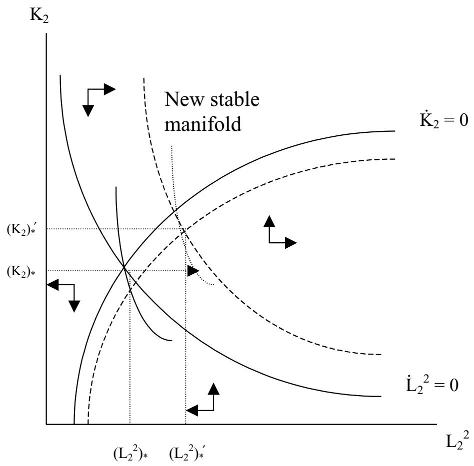

FIGURE A.3. Dynamics without specialization: Phase diagram after A_{P} increase.

$$\frac{\dot{L}_{\mathrm{R}}^{2}}{L_{\mathrm{R}}^{2}} = \frac{\left[(1-\theta)\left(A_{\mathrm{P}}L_{\mathrm{P}}-m_{\mathrm{P}}\right)+\left(A_{\mathrm{R}}^{1}L_{\mathrm{R}}-m_{\mathrm{R}}\right)\right]-A_{\mathrm{R}}^{1}L_{\mathrm{R}}^{2}}{\beta\left[(1-\theta)\left(A_{\mathrm{P}}L_{\mathrm{P}}-m_{\mathrm{P}}\right)+\left(A_{\mathrm{R}}^{1}L_{\mathrm{R}}-m_{\mathrm{R}}\right)\right]+(1-\beta)\,A_{\mathrm{R}}^{1}L_{\mathrm{R}}^{2}}$$
$$\cdot\left\{[\rho+(1-\beta)\,\delta]-\frac{\beta\,(1-\beta)\,(1-\theta)}{\theta}A_{\mathrm{R}}^{2}\left(\frac{L_{\mathrm{R}}^{2}}{K_{\mathrm{R}}}\right)^{1-\beta}\right.$$
$$\left.\times\left[\frac{\left(A_{\mathrm{P}}L_{\mathrm{P}}-m_{\mathrm{P}}\right)+\left(A_{\mathrm{R}}^{1}L_{\mathrm{R}}-m_{\mathrm{R}}\right)}{A_{\mathrm{R}}^{1}L_{\mathrm{R}}^{2}}-1\right]\right\}. \qquad \textbf{(A.6)}$$

These equations yield the following expressions for the steady state:

$$\left(\frac{K_{\mathrm{R}}}{L_{\mathrm{R}}^{2}}\right)_{*}^{1-\beta}=\frac{\beta A_{\mathrm{R}}^{2}}{\rho+\delta}$$

$$(K_{\mathrm{R}})_{*,\mathrm{NS}}=\left(\frac{\beta A_{\mathrm{R}}^{2}}{\rho+\delta}\right)^{\frac{1}{1-\beta}}\left\{\frac{(1-\theta)\left(A_{\mathrm{P}}L_{\mathrm{P}}-m_{\mathrm{P}}+A_{\mathrm{R}}^{1}L_{\mathrm{R}}-m_{\mathrm{R}}\right)}{A_{\mathrm{R}}^{1}\dfrac{(1-\beta)\,(\rho+\delta)\,+\beta\rho\theta}{(1-\beta)\,(\rho+\delta)}}\right\}.$$

A.5. PROOF OF CLAIM 6

To draw the phase diagram for the dynamic system given in (A.5) and (A.6), note that the $\dot{K}_{\mathrm{R}}=0$ locus is

$$K_{\mathrm{R}}=\left(\frac{1}{\delta}\right)^{\frac{1}{1-\beta}}\left\{1+(1-\beta)\left(\frac{1-\theta}{\theta}\right)A_{\mathrm{R}}^{2}\left(L_{\mathrm{R}}^{2}\right)^{1-\beta}\right.$$
$$\left.-\left(\frac{1-\theta}{\theta}\right)(1-\beta)\left[A_{\mathrm{P}}L_{\mathrm{P}}-m_{\mathrm{P}}+A_{\mathrm{R}}^{1}L_{\mathrm{R}}-m_{\mathrm{R}}\right]\left(\frac{A_{\mathrm{R}}^{2}}{A_{\mathrm{R}}^{1}}\right)\left(\frac{1}{L_{\mathrm{R}}^{2}}\right)^{\beta}\right\}^{\frac{1}{1-\beta}}.$$

https://doi.org/10.1017/S1365100507060166 Published online by Cambridge University Press

It is increasing in L_R^2. The $\dot{L}_R^2 = 0$ locus is

$$K_R = \frac{\beta(1-\beta)(1-\theta)}{\theta[\rho + (1-\beta)\delta]} A_R^2 \left[\frac{(A_P L_P - m_P) + \left(A_R^1 L_R - m_R\right)}{A_R^1 \left(L_R^2\right)^{\beta}} - \left(L_R^2\right)^{1-\beta} \right]^{\frac{1}{1-\beta}},$$

It is decreasing in L_R^2. The stable manifold is downward-sloping. The phase diagram before and after A_P increases is shown in Figure A.3.

When A_P increases $(K_R)_*$, $(L_R^2)_*$ increase (both by the same factor, to keep K_R/L_R^2 and thus p unaltered). Both loci shift outward. The dotted lines show the new loci and the stable manifold. K_R cannot jump at the time of increase in A_P. But L_R^2 does; in fact it overshoots and decreases along the new manifold to its new steady-state value. K_R increases to its new steady state value along the new stable manifold. Equation (28) shows that the price p also jumps.