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Productivity growth and convergence in crop, ruminant, and nonruminant production: measurement and forecasts

Carlos E. Ludena[a,*], Thomas W. Hertel[b], Paul V. Preckel[b], Kenneth Foster[b], Alejandro Nin[c]

[a]*Agricultural Development Unit, Production, Productivity and Management Division ECLAC—United Nations, Dag Hammarskjold 3477, Vitacura Casilla: 179-D, Santiago de Chile, Chile*

[b]*Department of Agricultural Economics, Purdue University, 403 West State Street, West Lafayette, IN 47907, USA*

[c]*International Food Policy Research Institute (IFPRI), 2033 K Street NW, Washington DC 20006, USA*

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Abstract

Projections of future productivity growth rates in agriculture are an essential input for a great variety of tasks, ranging from development of an outlook for global commodity markets to the analysis of interactions between land use, deforestation, and ecological diversity. Yet solid projections for these variables have proven elusive—particularly on a global basis. This is due, in no small part, to the difficulty of measuring historical total factor productivity growth. Consequently, most productivity projections are based on partial factor productivity measures that can be quite misleading. The purpose of this work is to provide worldwide forecasts of agricultural productivity growth till the year 2040 based on the latest time series evidence on total factor productivity growth for crops, ruminants, and nonruminant livestock. The results suggest that most regions in the sample are likely to experience larger productivity gains in livestock than in crops. Within livestock, the nonruminant sector is expected to continue to be more dynamic than the ruminant sector. Given the rapid rates of productivity growth observed recently, nonruminant and crop productivity in developing countries may be converging to the productivity levels of developed countries. For ruminants, the results show that productivity levels in developing countries are likely to be diverging from those in developed countries.

JEL classification: D24, O13, O47, Q10

Keywords: Total factor productivity; Projections; Convergence; Crops; Livestock; Malmquist index

1. Introduction

Whether one is interested in the outlook for global commodity markets (OECD-FAO, 2006; USDA, 2006), future patterns of international trade (Anderson et al., 1997), or the interactions between land use, deforestation, and ecological diversity (Ianchovichina et al., 2001), the rate of productivity growth in agriculture is an essential input. The past, present, and future of agricultural productivity has long been of interest to agricultural economists. More than 200 years ago, Malthus (1798) predicted that population would outrun food supply. But at the time, most increases in agricultural production occurred at the extensive margin—through cultivated area. Over the last century, most increases in production have come from increased agricultural productivity, which permitted the world to sustain an adequate aggregate food supply, thereby avoiding prolonged famine. However, this transition from a natural-resource-based to a science-based system has been uneven across countries. In fact, the slowest rate of productivity growth has occurred on the continent with the highest rate of population growth—Africa. Therefore, it is important to know whether less productive countries might converge to the productivity levels of the most productive countries, and if so, how fast is this likely to occur. Yet solid projections for this variable have proven elusive, particularly on a global basis.

The purpose of this article is to present the latest time series evidence on global *total* factor productivity (TFP) growth for disaggregated agricultural subsectors, including crops, ruminants, and nonruminant livestock. We then follow with tests for convergence amongst regions, and provide forecasts for farm productivity growth till the year 2040. As a consequence, this article offers three significant improvements over previous research. First, it offers the first set of *disaggregated* TFP measures for global livestock, thereby extending the work of Nin et al. (2003). It turns out that this disaggregation is essential,

*Corresponding author. Tel.: (56-2) 210-2595; fax: (56-2) 210-2590.
E-mail address: carlosludena@yahoo.com (C. Ludena).

because the patterns of productivity growth are fundamentally different between ruminant and nonruminant livestock in developed and developing countries. Second, it provides agricultural productivity convergence results and forecasts on a global basis using TFP measures. This is an improvement from current productivity forecast studies. Those studies use partial factor productivity (PFP) measures (i.e., yield), which are an inaccurate measure of productivity. Finally, it provides for the first time a set of comprehensive, disaggregated TFP forecasts for global agriculture over the next 40 years.

Productivity measurement in agriculture has been of enduring interest to economists. Coelli and Rao (2005) present a review of multicountry agricultural productivity studies, reporting a total of 17 studies in the decade between 1993 and 2003. The majority of these studies indicate technological regression for developing countries and technological progress for developed countries. Coelli and Rao, however, find that there has been technological progress for all regions in the sample.

Most of the studies on productivity growth in agriculture have focused on sector-wide productivity measurement, with less attention to the estimation of subsector productivity. This omission is not because of a lack of interest, but of data availability on input allocation to individual activities. Because of this lack of information, subsector productivity has usually been assessed using PFP measures such as "output per head of livestock" and "output per hectare of land." However, PFP is an imperfect measure of productivity. For example, if increased output per head of livestock is obtained by more intensive feeding of animals, then TFP growth may be unchanged, despite the apparent rise in PFP. In general, the issue of factor substitution can lead PFP measures to provide a misleading picture of performance (Capalbo and Antle, 1988).

A more accurate measure of productivity growth must account for all relevant inputs, hence the name *total* factor productivity. The difficulty is that traditional TFP measurement requires complete information about the allocations of inputs to specific agricultural subsectors. For example, the researcher needs data about how much labor time was allocated to crop production and how much to livestock production for each unit (farm, household, country, etc.) under analysis. This level of disaggregation is seldom contained in primary data sets, let alone in secondary data at the national level. To overcome the lack of input allocation data, Nin et al. (2003) propose a directional Malmquist index that finesses unobserved input allocations across agricultural sectors. They use this methodology to generate multifactor productivity for crops and livestock. This technique will form the basis for the historical analysis presented in this article.

However, we first update and extend the work of Nin et al. (2003) to account for the wide differences in productivity growth among different species of livestock (Delgado et al., 1999; Nin et al., 2004; Rae and Hertel, 2000). Delgado et al. show that between 1982 and 1994, output per head in beef grew at 0.5%, milk grew at 0.2%, pork grew at 0.6%, and poultry grew at 0.7% per year. Rae and Hertel show that in Asia the rate of growth in this PFP measure for nonruminants (pigs and poultry) was sharply higher than the rate of productivity growth in ruminants (cattle, sheep, and goats). If these large differences in productivity also appear in TFP measures, then there is great potential to make erroneous inference about trade, development, and land-use questions associated with a failure to disaggregate livestock by type. Therefore, in this article, we extend the work of Nin et al. (2003) by disaggregating livestock productivity measures into ruminant and nonruminant measures using data for the period between 1961 and 2001 obtained from the United Nations Food and Agriculture Organisation (FAO).

A key part of this historical analysis is the decomposition of productivity growth into two components: technical change, or movement in the technology frontier for a given subsector, and "catching up," which represents improved technology bringing the country in question closer to the global frontier (Färe et al., 1994). We believe that forecasts of future productivity growth must distinguish between these two elements of technical progress, and this is reflected in our approach to forecasting future technology.

Productivity convergence is key in our analysis, because it provides an answer to the question of whether less productive countries are catching up to the most productive countries, and if so, how quickly? Having produced this historical time series for TFP by agricultural subsector, we then test for productivity convergence across regions, using time series techniques. These time series relationships also form the basis for our forecasts of productivity growth over the period 2001–2040.

The results suggest that most regions in the sample are likely to experience larger productivity gains in livestock than in crops. Within livestock, the nonruminant sector TFP growth is expected to continue to be larger than the ruminant sector. Given the rapid rates of productivity growth observed recently, nonruminant and crop productivity in developing countries may be converging to the productivity levels of developed countries. For ruminants, the results show that productivity levels may be diverging between developed and developing countries.

This article is divided into three major sections. The first section describes the TFP measurement methodology and data, and presents the historical TFP results between 1961 and 2000. The second section presents the methodology and convergence results of productivity growth across regions based on the historical TFP data from the first section. Finally, the third section presents the TFP projections methodology and results of our forecasts to the year 2040, based on the data and results from the first two sections.

2. Productivity measurement methodology and data

The Malmquist index is based on the idea of a function that measures the distance from a given input/output vector to the technically efficient frontier along a particular direction defined by the relative levels of the alternate outputs. Nin et al. (2003) modify the directional distance function measure (Chung et al.,

1997) for use in the measurement of agricultural subsector productivity. There are two features that distinguish their work from the general directional distance measure. The first is that the direction of expansion of outputs and contraction of inputs increases only the *i*th output while holding all other outputs and all inputs constant. The second is that physical inputs that can be allocated across outputs are treated as different inputs. That is, allocatable inputs are constrained individually by output, and inputs that are not allocable are constrained in aggregate. For example, land in pasture is a livestock input, and cropland is a crops input.

Following Färe et al. (1994), the product-specific directional Malmquist TFP index measures the TFP change between two data points by calculating the ratio of the distances to the frontier for a particular period of each data point. Nin et al. (2003) take advantage of information on input allocation by introducing specific input constraints for allocated inputs, modifying the directional distance function measure (Chung et al., 1997). In general, the distance function is defined simultaneously as the contraction of inputs and the expansion of output $(-\boldsymbol{g}_x \boldsymbol{g}_y)$, which in the case of a single output-oriented measure is denoted by $g = (y_i, \mathbf{0})$. The distance function $D(\mathbf{x}, \mathbf{y}; g = (y_i, \mathbf{0}))$ is the optimal objective value for the following problem:

$$\max_{z^k, \beta_i^{k*}} \beta_i^{k*}$$

subject to:

$$\sum_{k=1}^{N} z^k y_j^k \geq y_j^{k*} \qquad i \neq j \quad \text{and} \quad j = 1, 2, \ldots, J$$

$$\sum_{k=1}^{N} z^k y_i^k \geq y_i^{k*}\left(1 + \beta_i^{k*}\right)$$

$$\sum_{k=1}^{N} z^k x_{hj}^k \leq x_{hj}^{k*} \qquad h \in A$$

$$\sum_{k=1}^{N} z^k x_h^k \leq x_h^{k*} \qquad h \notin A$$

$$z^k \geq 0 \qquad k = 1, \ldots, N,$$

where k is the set of countries (k^* is the particular country for which the distance measure is being applied), j is the set of outputs, h is the set of inputs, z^k is the weight on the kth country's data, A is the set of allocatable inputs, x_{hj}^k is the level of the allocatable input h used to produce output j of country k, i is the particular output for which efficiency is being measured for country k^*, $i \neq j$ indexes the other outputs (for which efficiency is not being measured), and β is a scalar.

On the basis of the modified distance function, the product-specific Malmquist index between period s (the base period) and period t is defined as the geometric mean of two Malmquist indexes, one evaluated with respect to period s technology and one with respect to period t technology:

$$DM(s,t) = \left[\frac{\left(1 + \vec{D}_0^s\left(x^t, y_i^t, y_{-i}^t; y_i^t, \mathbf{0}\right)\right)}{\left(1 + \vec{D}_0^s\left(x^s, y_i^s, y_{-i}^s; y_i^s, \mathbf{0}\right)\right)} \cdot \frac{\left(1 + \vec{D}_0^t\left(x^t, y_i^t, y_{-i}^t; y_i^t, \mathbf{0}\right)\right)}{\left(1 + \vec{D}_0^t\left(x^s, y_i^s, y_{-i}^s; y_i^s, \mathbf{0}\right)\right)}\right]^{0.5}, \tag{1}$$

where $\vec{D}_0^s(x^t, y^t)$ represents the distance from the period t observation to the period s frontier. The output specific Malmquist index in Eq. (1) indicates that we measure TFP growth for output y_i^s, while holding all other outputs y_{-i}^s constant. This directional Malmquist index for country i is estimated by solving a series of four linear programming problems, two to obtain the distances of country i at time s and time t to the frontier at time s, and two to measure the distance of country i at time s and t to the frontier at t. The production possibility frontier is estimated by the solution of a sequence of linear programming problems, one for each country in the sample. The distance of each country i to the frontier is estimated as a by-product of the frontier estimation method. As with the Malmquist index, an index value greater than 1 indicates an increase in productivity from period s to t. This measure is decomposed into an efficiency component (catching up) and a technical change component (changes in the production frontier):

$$DEFF(s,t) = \frac{\left(1 + \vec{D}_0^t\left(x^t, y_i^t, y_{-i}^t; y_i^t, \mathbf{0}\right)\right)}{\left(1 + \vec{D}_0^s\left(x^s, y_i^s, y_{-i}^s; y_i^s, \mathbf{0}\right)\right)} \tag{2}$$

$$DTECH(s,t) = \left[\frac{\left(1 + \vec{D}_0^s\left(x^s, y_i^s, y_{-i}^s; y_i^s, \mathbf{0}\right)\right)}{\left(1 + \vec{D}_0^t\left(x^s, y_i^s, y_{-i}^s; y_i^s, \mathbf{0}\right)\right)} \cdot \frac{\left(1 + \vec{D}_0^s\left(x^t, y_i^t, y_{-i}^t; y_i^t, \mathbf{0}\right)\right)}{\left(1 + \vec{D}_0^t\left(x^t, y_i^t, y_{-i}^t; y_i^t, \mathbf{0}\right)\right)}\right]^{0.5}. \tag{3}$$

How much closer a country gets to the world frontier is called catching up and how much the world frontier shifts at each country's observed input mix is called "technical change" and "innovation." Once a country catches up to the frontier, further growth is limited by the rate of innovation, or movement of the frontier itself.

There are two important limitations of the directional Malmquist index, which must be noted at this point. The first is the case in which the distance function takes the value -1, in which case there is no feasible way to produce y_{-i}^s (the other outputs that are being held constant) given the basis for technology. This can happen when $s \neq t$ and is more likely in the case in which a future observation of the output vector (and associated input vector) is compared with a production possibilities frontier from the past. If there has been sufficient technical progress in the production of the other outputs, then there may be no way to produce the vector of other outputs for the given set of inputs based on technical possibilities from the past. We refer to this as the infeasibility problem, not because the linear program does not have a feasible solution, but because it is not feasible to produce any of the specific output while producing the observed quantities of the other outputs with the given input vector.

One approach to mitigation of this infeasibility problem is to use a cumulative frontier approach that assumes that all previous years of technology remain feasible (see Nin et al., 2003). This technology definition eliminates the possibility of technical regress (the frontier moving backwards) and reduces (but does not eliminate) the possibility of infeasibility of values of -1 for the distance function when comparing a future input/output vector with current production technology. In sum, the infeasibility problem when estimating the directional distance cannot be eliminated, but it can be reduced by the use of the cumulative technology. Hence, the infeasibility problem prevents the estimation of TFP changes for several countries in different periods, which in turn prevents us from building up weighted productivity measures for each region, as other authors have done (Coelli and Rao, 2005). In order to be able to report results for all regions of interest in this study, aggregated regions are included as production points in the technology and the Malmquist index is directly estimated for these aggregated regions together with the estimates of individual countries. Aggregation of regions has a tendency to reduce or eliminate extremes, resulting in more balanced output combinations, which we observe are far less likely to generate the infeasibility problem when estimating directional distances for these aggregated regions. In this instance, we were able to obtain a full-time series for every aggregated region in the efficiency measurement exercise. The individual country observations serve to identify the production possibilities frontier for agriculture, while the technical efficiency and technological change indexes are computed for aggregated regions.

The second limitation derives from the fact that there might be a factor reallocation bias in the measure; that is, we might mistake the movement of unallocated inputs from one activity to the other for technological progress in the benefiting activity. These limitations notwithstanding, we believe that this approach still offers a great improvement over the PFP alternative.

Data for inputs and outputs were collected principally from FAOSTAT 2004 and covered a period of 40 years from 1961 to 2001. The data included 116 countries (Table 1) considering three outputs (crops, ruminants, and nonruminants) and nine inputs (feed,[1] animal stock, pasture, land under crops, fertilizer, tractors, milking machines, harvesters, threshers, and labor). Crops include cereals, pulses, roots and tubers, and primary oils crops; ruminants include bovine cattle, sheep, goats, and camelids (both meat and milk production); nonruminants include pigs, poultry (chicken, duck, geese, turkey), eggs, rabbits, rodents, honey, and cocoons. Nin et al. (2003) note that there are two limitations to these data. First, there is limited information on prices, and second, input usage is not allocated across activities in agriculture. For this reason, the data are well suited to use in conjunction with the product-specific distance measure. This allows the estimation of productivity growth by subsector given the inputs used and the output of all other sectors given these data limitations.

To estimate the disaggregate TFP measures for crops, ruminants, and nonruminants, we assume five allocatable inputs: land under crops is allocated to crops, ruminant stock and milking machines to ruminants, nonruminant stock to nonruminants, feed is allocated to livestock but cannot be allocated between ruminants and nonruminants. All other inputs remain unallocated to outputs.

It is worth noticing that this work makes the effort to disaggregate agricultural output into three subsectors. As discussed by some authors, the apparent rate of productivity growth is to some degree dependent on the level of aggregation used. Input and output aggregation can have implications for measured productivity and efficiency, and can lead to nonmonotonicity. That is, for the same level of inputs, output can be higher for every country in period t than period $t-1$ yet aggregate productivity growth can fall. As noted by Preckel et al. (1997), these implications are ambiguous since firms (countries) that previously were efficient become inefficient and vice versa. This inconsistency in efficiency measures suggests that aggregation of variables should be avoided whenever possible. The same type of problem is introduced with country aggregation, where scale issues are a problem (Rao and Coelli, 2004).

3. Total factor productivity growth: historical results

The results of our TFP calculations are summarized in Table 2. We focus on historical productivity measurement and forecasts for eight regions of the world, as shown by the groupings of countries in Table 1. We report directional TFP measures for the crop, ruminant, and nonruminant subsectors of agriculture. For each agricultural subsector, Table 2 reports the estimated average change in TFP as well as the change in efficiency (EFF) and technical change (TCH) derived from the directional Malmquist index for two periods: 1961–1980 and 1981–2000, in order to examine changes in these growth rates over the four decades for which we have data.

The regional measures presented in Table 2 were obtained by combining individual country observations with regional observations, where the latter are treated as separate observations, obtained by aggregating inputs and outputs in individual countries within the regions (Table 2) using value share weights (see discussion in the previous section).

The world productivity estimates in Table 2, as well as those for aggregate agriculture, have been created as an adjusted share-weighted sum of the individual regions' crop, ruminant, and nonruminant productivity measures, also reported in

[1] Feed (expressed as quantity of protein in tons) is an input estimated using the quantity of edible commodities (crop and animal source) used as feed from FAO Food Balance Sheets and the protein content of each crop as in Nin et al. (2003).

Table 1
List of countries in FAO data

1. Industrialized countries	Australia, Austria, Benelux, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, U.K., U.S.A.
2. Economies in transition	Albania, Bulgaria, Czech Rep, Hungary, Poland, Romania, Slovakia, former USSR, former Yugoslav SFR
3. China	
4. East and South East Asia	Cambodia, Indonesia, Korea DP Rep, Korea Rep, Laos, Malaysia, Mongolia, Myanmar, Philippines, Singapore, Thailand, Vietnam
5. Asia developing	Bangladesh, Bhutan, China, Cambodia, India, Indonesia, Iran, Iraq, Jordan, Korea DP Rep, Korea Rep, Laos, Lebanon, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Saudi Arabia, Singapore, Sri Lanka, Syria, Thailand, Turkey, Vietnam, Yemen
6. Middle East and North Africa	Algeria, Egypt, Iran, Iraq, Jordan, Lebanon, Libya, Morocco, Saudi Arabia, Sudan, Syria, Tunisia, Turkey, Yemen
7. Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Rep, Chad, Congo Dem Rep, Congo Rep, Cote d'Ivoire, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Namibia Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
8. Latin America and Caribbean	Argentina, Belice, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Rep, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela

Table 2
Historical and projected average total factor productivity growth rates by region and sector, 1961–2040 (%)

Regions/sectors	Period	Crops			Ruminants			Nonruminants			Weighted average		
		TFP	EFF	TCH	TFP	EFF	TCH	TFP	EFF	TCH	TFP	EFF	TCH
World	1961–1980	0.49	−0.48	0.97	0.15	−0.63	0.80	1.50	−0.72	2.25	0.60	−0.55	1.16
	1981–2000	0.95	0.42	0.53	1.10	0.60	0.50	2.71	−1.43	4.23	1.29	0.13	1.18
	2001–2040	0.94	0.22	0.71	0.82	0.17	0.65	3.60	0.92	2.64	1.38	0.34	1.04
Industrialized countries	1961–1980	1.97	0.97	0.98	0.83	0.27	0.56	1.29	0.25	1.03	1.49	0.61	0.86
	1981–2000	0.97	0.09	0.88	0.59	−0.18	0.77	1.17	−0.97	2.18	0.89	−0.21	1.12
	2001–2040	1.14	0.21	0.93	0.27	−0.39	0.66	0.63	−0.94	1.61	0.77	−0.21	0.99
Economies in transition	1961–1980	0.50	−0.59	1.11	0.06	−0.31	0.38	0.75	−0.72	1.50	0.41	−0.53	0.95
	1981–2000	1.77	0.11	1.66	0.50	−0.06	0.56	1.65	−0.64	2.33	1.39	−0.04	1.43
	2001–2040	1.39	0.49	0.89	0.53	0.06	0.47	2.09	0.61	1.45	1.24	0.38	0.85
China	1961–1980	−0.03	−1.54	1.53	−0.88	−2.67	1.84	1.88	−1.61	3.55	0.48	−1.64	2.16
	1981–2000	1.52	1.45	0.07	6.67	6.59	0.07	4.81	−2.14	7.10	2.88	0.73	2.19
	2001–2040	1.45	0.64	0.80	3.01	2.04	0.95	6.60	2.58	3.91	3.11	1.33	1.75
East and South East Asia	1961–1980	0.63	−0.08	0.71	0.50	−0.49	0.99	1.74	0.05	1.69	0.78	−0.08	0.86
	1981–2000	−0.58	−0.67	0.10	−0.94	−1.31	0.38	0.77	−3.04	3.96	−0.40	−1.03	0.65
	2001–2040	−0.66	−1.06	0.40	−1.24	−1.91	0.69	3.67	0.84	2.80	−0.08	−0.83	0.75
South Asia	1961–1980	−0.37	−1.02	0.66	−0.69	−1.23	0.56	1.12	−0.53	1.66	−0.39	−1.05	0.67
	1981–2000	0.72	0.60	0.13	1.40	1.01	0.38	2.66	−1.01	3.73	0.94	0.64	0.30
	2001–2040	0.96	0.57	0.39	1.48	1.00	0.47	3.48	0.96	2.49	1.16	0.68	0.48
Middle East and North Africa	1961–1980	−0.15	−0.44	0.30	0.18	−0.44	0.62	1.14	0.32	0.82	0.04	−0.37	0.42
	1981–2000	0.09	−0.03	0.13	−0.22	−0.63	0.42	0.15	−0.75	0.92	0.03	−0.23	0.26
	2001–2040	0.45	0.23	0.21	−0.31	−0.83	0.52	−0.28	−1.12	0.87	0.22	−0.12	0.34
Sub-Saharan Africa	1961–1980	−0.57	−0.87	0.30	0.24	−0.33	0.57	0.62	0.34	0.28	−0.34	−0.69	0.35
	1981–2000	0.88	0.73	0.15	0.49	0.27	0.22	0.38	−0.84	1.24	0.77	0.54	0.23
	2001–2040	0.91	0.68	0.22	0.57	0.17	0.40	−0.05	−0.80	0.76	0.78	0.49	0.29
Latin America and Caribbean	1961–1980	0.46	−0.53	1.00	−0.45	−2.01	1.60	1.48	−1.44	2.97	0.38	−1.04	1.44
	1981–2000	1.06	−0.14	1.20	0.62	0.46	0.15	2.54	−0.30	2.84	1.16	−0.01	1.17
	2001–2040	0.62	−0.47	1.10	1.50	0.62	0.87	4.55	1.75	2.74	1.41	0.13	1.28

Note: Weighted average productivity growth rates are estimated using output shares of each subsector in agriculture in the base period, 2001.

Table 2.[2] The shares used in this process are based on the value of production in the year 2001, as reported by the FAO, and are available in Appendix A. We adjust these directional measures by a region-specific adjustment factor so that they are consistent with the aggregate agriculture productivity estimate calculated from the traditional Malmquist index. Not only does this ensure comparability with other studies of agricultural TFP, it also renders these estimates usable in projections frameworks that do not embody the directional productivity concept.

Obviously, the historical aggregate would be more accurate if we used observed, annual value weights. However, these are not available over the projections period, and time-varying weights would confound any attempt to compare the historical and projected aggregates. Not surprisingly, the industrialized countries and China dominate the 2001 shares used for aggregation purposes. They account for 28% and 23% of global agricultural output, respectively. China's agriculture is dominated by crops (63% of total value), whereas the industrialized countries have nearly a 50–50 split between crops and livestock.

Entries in the top right-hand corner in Table 2 suggest that global agricultural TFP growth has been increasing over time, rising from 0.60% per year in the 1960s and 1970s to 1.29% per year in the 1980s and 1990s, with an average rate of growth over the 1961–2000 period of 0.94% per year.[3] As we will see below, the increased productivity growth in the last two decades of the twentieth century is due to accelerating productivity growth in those developing regions where substantial economic reforms have taken place since 1980: China, Eastern Europe and the former Soviet Union, sub-Saharan Africa, and Latin America. TFP growth may be decomposed into that portion due to an outward shift in the production possibilities frontier and that due to the average degree of catching up of individual regions to this dynamic frontier. From the entries in the top right-hand corner of Table 2, it is clear that, taking into account the production-weighted averages of different regions/subsectors, the frontier in agriculture advanced more rapidly over 1960–1970s (1.16% per year) than individual regions' TFP, thereby leading to negative technical efficiency growth (−0.55% per year). However, for the 1980–1990s there has been catching up to frontier, denoted by a positive efficiency growth of 0.13% per year.

When we separate aggregate agricultural TFP growth into subsectors, we find that, for the world as a whole, nonruminant productivity growth far outpaced that in the other subsectors for both 20-year historical periods (1.5% per year for the 1960–1970s and 2.71% for the 1980–1990s). This high rate of TFP growth has been fueled by a rapidly advancing frontier resulting from increased production in controlled facilities and greater availability of protein feed supplements. Therefore, virtually all aggregate regions have fallen further away from the frontier (negative technical efficiency growth rates) over the 1961–2000 period.

In the case of ruminants, we observe the same pattern as with nonruminant livestock productivity growth in the 1960–1970s. This changed in the 1980–1990s, with some regions, especially China and South Asia, catching up to the frontier. Overall TFP growth in ruminants has been on average about 0.62% per year over the 40-year period, with larger growth in the 1980–1990s (1.1% per year).

For crops, TFP growth has picked up in the more recent period (0.49% for the 1960–1970s vs. 0.95% for the 1980–1990s). Once again, all of the developing country regions fell away from the frontier in the 1960–1970s. However, in the 1980–1990s there was catching up for some developing regions, especially China. The countries shaping the crops frontier for most of the years in the sample include the United States, Japan, the Netherlands, Denmark, Sweden, New Zealand, Argentina, Uruguay, Malaysia, and South Korea.

Next, we turn to a discussion of the block of entries in Table 2 representing TFP growth rates in the industrialized countries. It is quite striking that in these countries, where the share of consumer expenditure on food is relatively low and only a small portion of the labor force is employed in agriculture, productivity growth rates are much higher—27% above the world average (which itself includes these countries) for the full historical period. This higher growth rate is fueled strongly by high TFP growth in the crops subsector (1.97% per year for the 1960–1970s and 0.97% for the 1980–1990s). This is an extraordinarily high rate of TFP growth for a mature sector in mature economies, which testifies to the enormous productivity of the public and private investments in agricultural research over the past half century in these countries.

Industrialized country TFP growth in the crops sector is followed in size by nonruminants (more than 1% per year)—although this rate of TFP growth is lower than the world average. (Industrialized countries account for one-third of the value of world output in nonruminants.) The slowest rate of productivity growth in the industrialized countries' agricultural sector is for ruminants (0.71% per year on average over the two historical periods). Even so, TFP growth rate for ruminants in the industrialized countries is higher than for all other regions in the 1961–1980 period, and higher than all excepting China and South Asia in the more recent period.

The next region displayed in Table 2 represents the so-called "Economies in Transition" (EIT), which include eastern Europe and the former Soviet Union. As the names indicate, they represent a group of economies that have undergone substantial changes in the past one and a half decade, and this is reflected in their TFP growth record. Indeed, the 20 years of the 1960–1970s shows slow TFP growth in this region (0.41% per year). This is followed by some rapidly accelerating productivity growth

[2] An alternative would be to estimate TFP for aggregate agriculture directly using the same distance function approach, only now non-directional (since there is only one output involved). This is the approach of Nin et al., for example. While this would offer a preferred estimate of aggregate agriculture productivity, it has a significant drawback for present purposes; namely, it is inconsistent with our subsector measures. Therefore, we opt to report aggregate agricultural productivity using the weighted subsector measures in order to offer a more consistent analysis of TFP growth worldwide, building up from the subsector level.

[3] See Ludena et al. (2006) for a more detailed breakdown of these historical growth rates, as well as the subsequent forecasts.

in the 1980–1990s, (1.39% per year), following the collapse of the Soviet Union and the opening up of the Eastern Bloc. This acceleration is particularly striking in the case of crops and nonruminant livestock production.

Productivity growth in China has been notoriously hard to measure due to the tendency for output statistics to be artificially inflated in order to meet pre-established planning targets. However, there is little doubt that the TFP performance of agriculture in China has been strengthening since the 1960s and 1970s when it grew at an average rate of nearly 0.48% per year. This improvement is particularly striking in the case of livestock production, where productivity growth in the 1980s and 1990s has been extraordinarily high (6.67% per year for ruminants and 4.81% for nonruminants). In the case of nonruminant production, we attribute most of this TFP growth to catching up due to increased adoption of confined production systems by Chinese pork and poultry producers. On the other hand, growth in ruminant productivity in China appears to have been driven by outward movement in the technological possibilities facing this sector.

China is followed in Table 2 by East and Southeast Asia. This regional grouping reflects FAO data on 14 countries, including much of ASEAN as well as both Koreas (see Table 1). As such, it is a rather heterogeneous grouping of economies, for which crop production is dominant. We estimate a slowing down of TFP growth for this region, with negligible growth in TFP in the 1980–1990s, fueled by negative TFP growth in crops and ruminants. Nonruminant productivity growth is the only bright spot for this region, but even here the annual rate of growth in TFP has fallen from 1.74% in the early period to 0.77% in the 1981–2000 period.

The next region in Table 2 is South Asia. Because the efficiency series for this region resulted in a value of 1 for all years in the sample, it was not possible for us to model these series using the logistic function analysis discussed later in the article. To solve this problem, we estimated this block using a composite of all developing countries in Asia. Therefore, it includes the preceding two regions (China, East and Southeast Asia, as well as South Asia and several countries in the Near East). This is clearly a limitation of the present study, but it does permit us to obtain an exhaustive set of estimates for the world as a whole, which is our ultimate goal. For this aggregate region, we find increasing productivity growth in crops and ruminant livestock, with faster growth in nonruminants in the last two decades. We assign these rates to South Asia in our subsequent analysis and projections.

The Middle East and North Africa is the next region covered by our estimates in Table 2. Much like South and Southeast Asia, the lack of growth in crop and ruminant TFP leads to negligible aggregate productivity growth with nonruminants being the only subsector with a reasonably strong performance over the historical period.

In contrast to the Middle East and North Africa, sub-Saharan Africa shows modest TFP growth across all three subsectors, with a marked improvement in crops productivity since the structural adjustment reforms of the 1980s. In fact, the overall weighted average rate of productivity growth for this region over the 1980–1990s is 0.77% per year.

The Latin America and Caribbean region also shows accelerating growth in TFP—particularly in the 1980s and 1990s when Brazil, in particular, undertook major rural sector reforms. This jump in TFP growth is most noticeable in crops and nonruminants. The overall average rate of productivity growth across all subsectors is 1.16% per year in this region over the more recent, 1981–2000, period.

4. Analysis of historical productivity growth: testing for convergence

Productivity convergence occurs when the less developed economies experience faster TFP growth than their developed neighbors, therefore reducing the technological gap between them. The concept of convergence can be traced back to Solow's (1957) neoclassical growth model that proposes technological change to be an exogenous process transferable from developed to developing countries. More recently, the endogenous growth theory (Lucas, 1988; Romer, 1986) considers technological change as a dynamic process, reflecting structural differences across countries. This model allows for productivity growth (and income) to differ permanently across countries, arguing that there may not be convergence between developed and developing countries due to structural impediments to complete convergence.

Convergence in agricultural productivity across countries has been tested by various authors. Suhariyanto and Thirtle (2001) find no evidence of convergence among 18 Asian countries. Schimmelpfennig and Thirtle (1999) and Rezitis (2005) find evidence of productivity convergence in agriculture between the United States and European countries using time series tests. Rao and Coelli (2004) and Coelli and Rao (2005) find that countries that were less efficient in 1980 have a higher TFP growth rate than those countries that were on the frontier in 1980. They conclude that these results indicate a degree of catch-up due to improved technical efficiency along with growth in technical change. However, as can be seen from Fig. 1, it makes little sense to test for convergence in aggregate agricultural TFP given the wide differences in subsector performance.

Rae and Hertel (2000) examine subsector convergence using PFP measures (livestock output per head) across a range of countries in the Asia-Pacific region. They find productivity convergence for pigs, poultry, and ruminant productivity, but divergence for milk productivity. Of course, this work is subject to the same criticism of all PFP measures; namely, it fails to distinguish between factor substitution and TFP growth. To the extent that increased output per head is due to higher feed use, TFP growth will be overstated.

There are two dominant approaches to testing for convergence: the cross-section and the time series approaches. The cross-section approach takes advantage of the tendency of developing economies to grow faster relative to the more developed economies. The time series approach (Bernard and Durlauf, 1995; Bernard and Jones, 1996) is based on the properties of the productivity growth series. In this case, there is convergence if the productivity differences across countries tend to zero, as the forecasting horizon tends to infinity. That is, there is productivity equality across countries or regions.

However, the time series approach requires us to have explicit measures of the level of productivity, not just the rate of growth. Therefore, we are confined to looking at convergence in efficiency levels only (Cornwell and Watcher, 1999). Cornwell and Watcher argue that these efficiency levels can be interpreted as the county's ability to absorb technological innovations and therefore represent productivity catch-up to the frontier by technology diffusion. This would allow us to test for convergence in the efficiency levels across regions.

We use these convergence tests to formally examine the hypothesis that there exists a common trend for subsector efficiency levels across regions. The first step in testing for convergence is to conduct augmented Dickey–Fuller tests on each of the calculated efficiency series to determine their long-run properties. For those regions whose measured efficiency is nonstationary we proceed to the second step, which involves testing for cointegration using the methodology developed in Johansen (1991) and Johansen and Juselius (1990). If a linear combination of two or more nonstationary series is stationary, then these series are said to be cointegrated. If the region-wise efficiency levels are cointegrated, that would indicate a long-term relationship in the diffusion of technology between those regions. This is precisely the kind of link in TFP across regions that we anticipate.

5. Convergence results

The augmented Dickey–Fuller tests (not shown here) indicate that, except for North America, Australia, New Zealand, and South Asia, the hypothesis of unit root nonstationarity at zero frequency cannot be rejected. Consequently, these series with suspected unit roots will be treated as nonstationary and potentially subject to cointegration. With the nonstationary series we apply cointegration tests, results for which are reported in Table 3. This table contains the results of the cointegration tests for each pair of countries/regions for crops, ruminants, and nonruminants, in that order.

Each cell in this table has three entries referring to the results of convergence tests for crops, ruminants, and nonruminants. Consider, for example, the entries in the China row, under the second column of Table 3. Here, the 5 in the first entry denotes convergence with developed countries in crop productivity levels at 5% significance, but shows no cointegration (no entry) for ruminants and nonruminants. In the case of Latin America, there is a 1 in the first entry of the developed countries row, denoting convergence at the 1% significance level. This suggests a regular, long-run pattern of technology diffusion of crop production technology from the developed countries to these two developing regions. There is also convergence of sub-Saharan Africa's crop TFP to the EIT, North Africa and the Middle East, Asia and Latin America.

For ruminants, the second entry in each cell of Table 3, most of the developing regions (China included) show convergence with the world average, although none show convergence with developed countries as a group. So, given the productivity growth rates that we have presented in this article, there may well be divergence between developed and developing countries in ruminant production. This is consistent with the earlier findings of Rae and Hertel (2000), based on convergence tests using PFP measures.

For nonruminants, the third entry in each cell, we observe that there is convergence of EIT and Latin America to developed countries, and, in the case of Latin America, convergence to Western Europe. Sub-Saharan Africa shows signs of convergence to various regions, including Europe, Asia, and Latin America. These results may suggest that for developing countries, the growth in nonruminant productivity is prompting them to catch up with developed countries.

Table 3
Cointegration results for each pair of regions and countries for crops, ruminants, and nonruminants efficiency levels

Country/region	World	Developed countries	Developing countries	Western Europe	Economies in transition	North Africa and Middle East	East and Southeast Asia	Latin America	Sub-Saharan Africa
China	-,5,-	5,-,-	—	—	-,-,5	—	—	—	—
World		—	-,5,-	-,5,5	-,1,-	—	—	-,5,5	-,5,-
Developed countries			—	-,-,5	-,-,5	—	—	1,-,5	—
Developing countries				—	—	5,-,-	—	5,-,1	—
Western Europe					—	5,-,-	—	5,-,5	-,-,1
Economies in transition						—	—	-,5,-	5,-,-
North Africa and Middle East							—	5,-,-	5,-,-
East and Southeast Asia								-,-,5	5,-,5
Latin America									5,-,1

Note: Each cell denotes the significance level of the cointegration test for crops, ruminants, and nonruminants, in that order. A dash denotes no cointegration. For example, in the pair developed Countries/Latin America, 1,-,5 denotes cointegration at the 1% level for crops, no cointegration for ruminants, and at the 1% level for nonruminants.

6. Productivity projections, 2001–2040

Before considering our own projections of agricultural productivity growth, it is useful to consider the approaches currently in use. One of the most widely cited models for forecasting future supply and demand of food products is the IMPACT model (Rosegrant et al., 2001), which covers 18 commodities and 37 countries or country groups. Future supply in this model is based on changes in area, yield and production in crops, and, in the case of livestock, changes in output per head and production. Productivity growth in this model is an exogenous trend factor in the PFP response function.

The USDA (2006) also makes projections of future supply and demand for agricultural products. They assume that historical growth trends in productivity hold for the period 2006–2015. The OECD-FAO Agricultural Outlook (2006) also assumes that productivity trends will continue over the period 2006–2015. They note that while production is projected to increase, some slowdown in the rate of growth is expected matching the slowdown in population growth. They expect that production growth in developing countries will outpace that in OECD countries, especially for meat and dairy products.

In constructing our forecasts of future productivity levels in agriculture, we depart in two significant ways from this current "state of the art." First, rather than forecasting PFP, we forecast TFP, building on our historical measures of TFP by the eight major regions of the world previously identified. Second, rather than simply extrapolating based on past trends, we recognize that there are two important contributors to historical productivity growth: technical change and technical efficiency, and these may behave quite differently over our forecast period. While we have no economic reason to argue against continued outward movement in the technology frontier in line with historical trends, we feel strongly that the process of catching up to the frontier, in which some developing countries are currently engaged, is unlikely to continue unabated. The simple reason for this is that in cases such as China's catching up to the frontier in ruminant livestock production, they will eventually reach the frontier. At that point, China's productivity growth may be expected to slow down, with future growth constrained by outward movement in the technological frontier.

To project changes in the technical efficiency component of TFP growth, we assume that technological catch up can be modeled as a diffusion process of new technologies, where the cumulative adoption follows an S-shaped curve (Griliches, 1957; Jarvis, 1981). This curve denotes that efficiency change at the beginning is slow because new technologies take some time to be adopted. As technology becomes more widely accepted, a period of rapid growth follows until it slows down again and an upper asymptote. In this case, we assume that efficiency levels for all regions will eventually reach the production possibility frontier and become fully efficient.

We follow Nin et al. (2004) in modeling this adoption path using a logistic functional form to capture the catching-up process for each of the countries/regions in the sample. Specifically, we use the following logistic function to represent the catching-up process of each of the regions in the sample:

$$Z_{it} = \frac{K_t}{1 + e^{-\alpha-\beta t}}, \tag{4}$$

where Z_{it} is the efficiency level of region i in year t, K_t is the maximum efficiency level, which in our case is equal to 1 and constant, and the parameters α and β determine the shape of the logistic function. The speed of change of the function is given by the value of β, where a higher value of β denotes a faster rate of catching up to the frontier. The parameters of the logistic function are estimated by transforming the observed efficiency values as follows:

$$Y_{it} = \log\left(\frac{Z_{it}}{K_t - Z_{it}}\right) = \alpha + \beta t. \tag{5}$$

Positive and significant estimates of β for a particular region will denote that this region is catching up to the frontier.

As in Nin et al. (2004), before estimating the logistic function, we perform Chow tests of structural breaks of the efficiency time series. With this, we account for historical changes in the efficiency series that may cause possible differences in the intercept or the slope or both. The estimates of the logistic function are then used to estimate the long-run path of efficiency levels out to the year 2040. These logistic function estimates are available in Appendices B–D.

We must also project the rate of technical change in future TFP growth. Here, we simply assume that countries grow at their historical trends. However, in the case of those regions with average growth rates higher than industrialized countries, the rate of future technical change is assumed to erode (linearly) over time so that it eventually falls to the industrialized country growth rate. In particular, we assume that, after 20 years, the regions with initial rates of technical change above the industrialized countries will be growing at the same rate as industrialized countries (otherwise, they would eventually exceed the productivity levels in the developed countries). Given the projected growth path of each of these two components of TFP, we calculate the TFP growth rates by multiplying the two components together, as was done with the calculation of the Malmquist index (Eq. (1)).

7. Projection results

The lower portion of each regional panel in Table 2 contains the TFP, efficiency, and technical change projections for each subsector in each region over the period 2001–2041. The first thing to note is that the annual weighted average for the world is higher in the projections period than in the historical period for TFP (1.38% vs. 1.29% for the most recent 20-year period, and just 0.60% for the 1961–1980 period). We see that this higher TFP growth projection is not driven by technical change, as this is actually lower in the projections period due to the anticipated slowing down of the very high rate of future technological change in a few key developing countries as discussed in the preceding paragraphs. The higher worldwide TFP average growth rate in the projections period is driven instead by an increased contribution from efficiency gains, relative to the historical period.

As we move to the left in the top panel of Table 2, we see which subsectors contribute the most to this higher rate of average TFP growth for agriculture. The overall average TFP growth rate for crops and ruminants is lower in the projections period than in the last 20-year historical period. However, nonruminants show a much higher TFP growth rate over the projections period. As anticipated above, this is fueled by high rates of catching up as predicted by our logistic model of technical efficiency. This catching up is particularly prominent in the first decade of the forecast period (see Ludena et al., 2006, for more details). So, in the aggregate, the big difference in the global TFP projections derives from advances in nonruminant technical efficiency.

Next, consider the TFP forecasts for industrialized countries. Here, the growth rate is lower than in the historical periods (0.77% vs. 1.49% in the 1961–1980 period and 0.89% in the 1981–2000 period) because of a slower rate of overall technical efficiency growth. The livestock sectors, in particular, show lower TFP growth in the industrialized countries over the forecast period.

In the case of the EIT region, much of the historical TFP growth was attributed to technological progress. As a consequence, if we project these historical growth rates forward without modification, TFP in the EIT region would eventually overtake that in Western Europe and the United States. Therefore, we impose the condition that, by 2020, the rate of technological change in the EIT will have fallen to the rate observed for industrialized countries. Thus, for crops, the EIT rate of technological progress from 2021–2040 is just 0.74% per year. However, when combined with a higher rate of growth in technical efficiency, the resulting overall TFP growth rate for EIT still exceeds that in industrialized countries (agriculture-wide annual weighted average of 1.24% vs. 0.77% for the industrialized countries).

China's TFP growth rate in the projections period continues at a rapid rate. However, with the exception of nonruminants, the TFP growth for the next 40 years is lower than that for 1981–2000 period. The main difference is the projected rate of growth in technical efficiency that is for nonruminants where TFP growth over the past two decades has been in nearly 5%, and the projected annual TFP growth rate is higher than 6%. This is fueled by the anticipated transition from backyard pig and poultry production systems to modern, confined production systems.

In East and Southeast Asia, projected weighted average productivity growth for all of agriculture is −0.08% with positive TFP growth rate (3.67%) only for nonruminants. The projections for South Asia, based on the entire developing Asia region, are higher than the historical estimates, with the highest growth rates for nonruminant livestock. For Middle East and North Africa, projected annual TFP for all three subsectors is 0.22%,

Table 4
Historical and projected world productivity growth shares by region and sector

Regions	Crops			Ruminants			Nonruminants		
	TFP	EFF	TCH	TFP	EFF	TCH	TFP	EFF	TCH
Productivity growth 1961–2001	*0.72*	*−0.03*	*0.75*	*0.62*	*−0.03*	*0.65*	*2.10*	*−1.08*	*3.23*
Shares by region (%)									
Industrialized countries	46	−355	28	47	−67	42	20	11	17
Economies in transition	13	57	15	5	78	9	4	4	4
China	24	39	24	35	−499	11	61	67	63
East and Southeast Asia	0	100	5	−1	47	2	3	7	5
South Asia	4	95	8	8	56	10	2	2	2
Middle East and North Africa	0	34	1	0	83	4	1	0	1
Sub-Saharan Africa	1	14	2	3	5	3	0	0	0
Latin America and Caribbean	12	116	17	2	396	20	9	8	9
Total	100	100	100	100	100	100	100	100	100
Productivity growth 2001–2040	*0.94*	*0.22*	*0.71*	*0.82*	*0.17*	*0.65*	*3.60*	*0.92*	*2.64*
Shares by region (%)									
Industrialized countries	28	22	29	14	−91	42	6	−35	20
Economies in transition	12	17	10	8	4	9	4	5	4
China	36	66	26	28	91	11	70	108	57
East and Southeast Asia	−6	−42	5	−2	−16	2	5	5	6
South Asia	15	38	8	24	77	10	2	2	2
Middle East and North Africa	2	5	1	−2	−21	4	0	−3	1
Sub-Saharan Africa	6	19	2	3	5	3	0	−2	0
Latin America and Caribbean	8	−25	18	26	52	20	12	19	10
Total	100	100	100	100	100	100	100	100	100

Note: Historical and projected shares are weighted by output value in 2001.

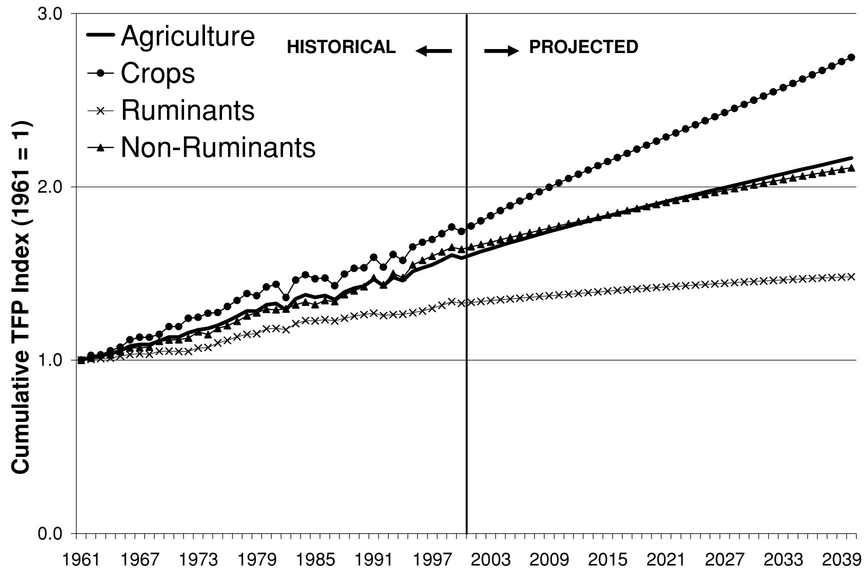

Fig. 1. Industrialized countries (1961–2040): cumulative Malmquist index in agriculture and subsectors.

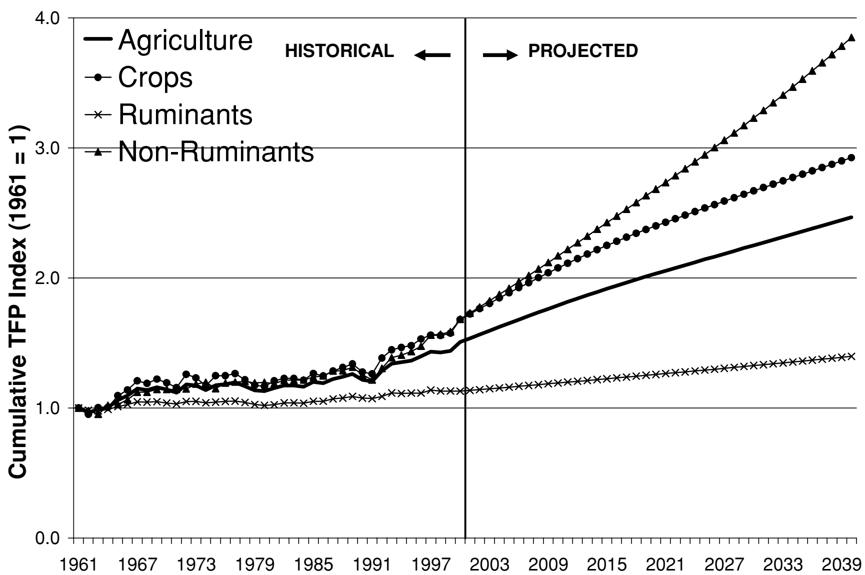

Fig. 2. Transition markets (1961–2040): cumulative Malmquist index in agriculture and subsectors.

with higher growth in crops (0.45%). In sub-Saharan Africa, average agricultural TFP growth over the next 40 years is projected to be just over 0.75%, fueled both by modest outward shifts in the frontier and improved efficiency. Subsector TFP growth in nonruminants is negative over the projections period, whereas TFP growth in crops is close to 1% per year.

Finally, for Latin America, projected average agricultural TFP growth is higher than historically observed, with the difference largely driven by livestock productivity growth. The annual weighted average of subsector productivities for this region is projected to grow at 1.61% per year over the 2001–2010 period, falling to 1.3% per year in the final 20 years, for an overall annual average of 1.41% over the next 40 years. As with the other regions, this future slowdown is due to decline in the growth rate of technical efficiency as producers move closer to the frontier. The ordering of subsector growth rates also follows the other developing country regions, outside of Africa, with nonruminant TFP growing fastest, followed by ruminants and then crops TFP growth.

Table 4 reports the contribution of each region to world TFP growth, by subsector for both 40-year historical and projections periods. These contributions represent the share-weighted TFP growth rates, by region, from Table 2, where weights are the same 2001 production shares used in Table 2 and reported

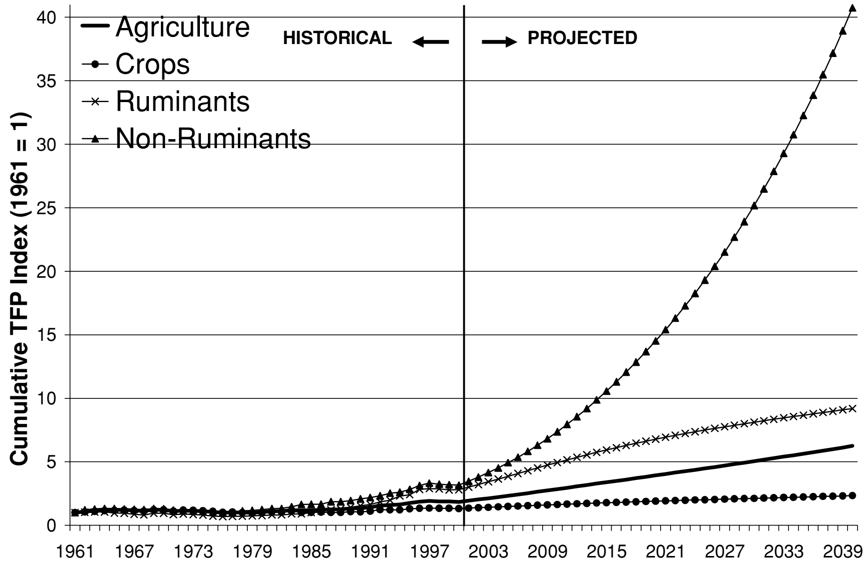

Fig. 3. China (1961–2040): cumulative Malmquist index in agriculture and subsectors.

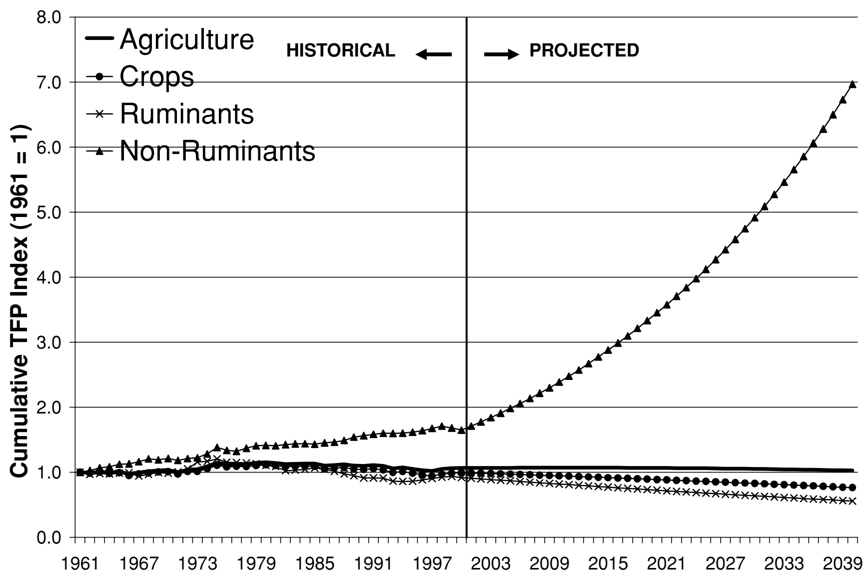

Fig. 4. East and Southeast Asia (1961–2040): cumulative Malmquist index in agriculture and subsectors.

in Appendix A. This table sheds some light on the sources of global average growth between the last 40 years and the projected 40-year period. As noted previously, TFP growth in crops between the two periods is just 0.22% per year higher in the projected period. However, whereas industrialized countries accounted for 46% of this TFP growth over the 1961–2000 period, they account for only 28% of the global productivity growth in crops over the next 40 years. (This uses constant production weights (2001); if we were to use annual production weights, this difference would be even more striking.) China's contribution to global crop TFP growth increases from 24% to 36%, and the contribution of other developing countries also increases strongly.

In the case of ruminants, the shift in relative contributions is even more striking, with industrialized countries' share of growth falling from 47% to 14%. China, South Asia, and Latin America make up the bulk of this difference. Overall, the average TFP growth rate for ruminants is also higher in the projections period. Asia as a whole accounts for about half of the efficiency gains in ruminant production, while almost half of the technical change gains are in industrialized countries. This indicates the leading role of industrialized countries as a source of

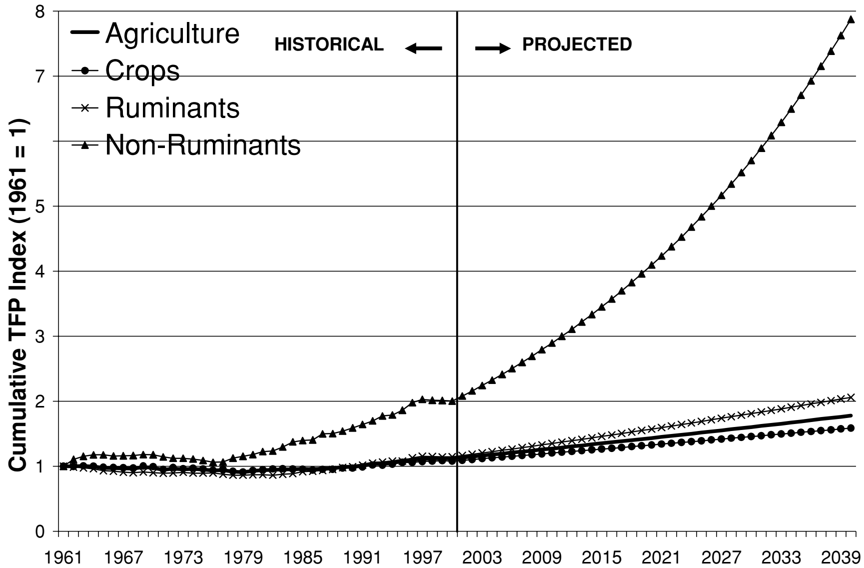

Fig. 5. South Asia (1961–2040): cumulative Malmquist index in agriculture and subsectors.

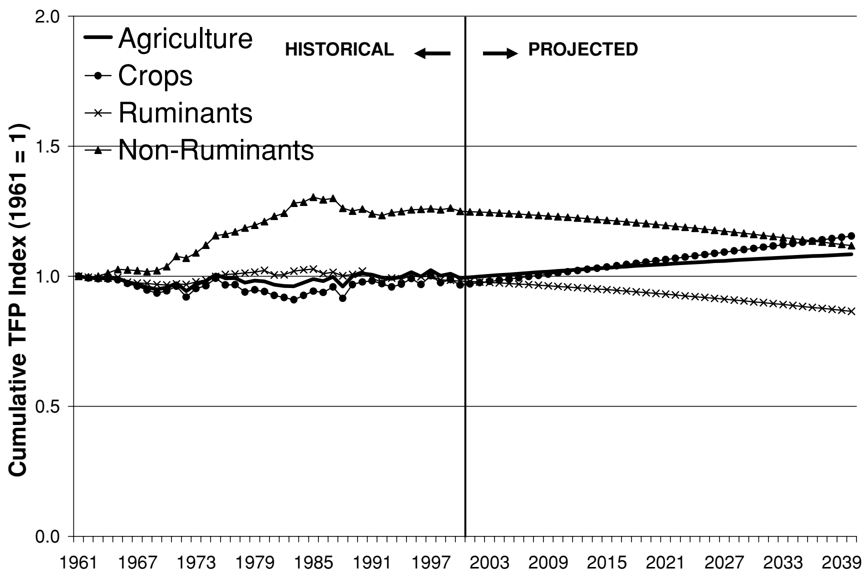

Fig. 6. Middle East and North Africa (1961–2040): cumulative Malmquist index in agriculture and subsectors.

technology in ruminant production, while most of the catching up is in developing regions, especially Asia.

In the case of nonruminants, projected TFP growth is dominated by China, which accounts for 70% of the global average TFP growth in this sector (vs. 61% in the historical period—China's 2001 production share is 38%) and 108% of the growth in technical efficiency. The nature of pigs and poultry technology makes it easily transferable across countries. As China expands its production from a backyard system, which is the dominant production system now, to more specialized production systems, these structural changes in production will have important impacts on costs and technology transfer that are reflected in these expected productivity and efficiency gains.

A useful way of summarizing the TFP information in Table 2 is via line graphs. We have done so in Figs. 1–8, which display the cumulative Malmquist TFP index for each subsector, as well as for the overall average, for both the historical and projected periods. The first thing to note from these figures is the heterogeneity across subsectors in each region. Taking an average, or simply measuring TFP at the level of aggregate agriculture is highly misleading if one is attempting to understand changes in commodity supplies or input use over time. These figures also permit one, in the historical period, to more readily identify the

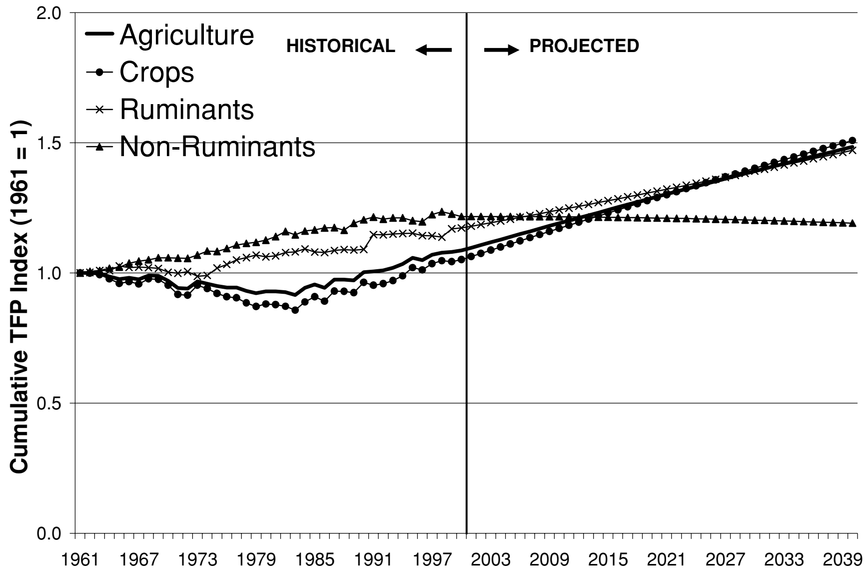

Fig. 7. Sub-Saharan Africa (1961–2040): cumulative Malmquist index in agriculture and subsectors.

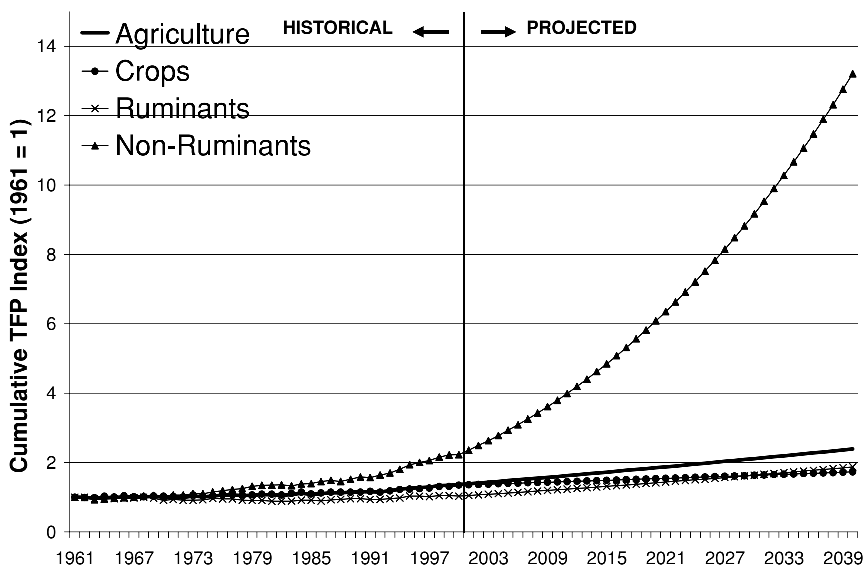

Fig. 8. Latin America and the Caribbean (1961–2040): cumulative Malmquist index in agriculture and subsectors.

impact of economic reforms—such as those in China in the late 1970s and those in sub-Saharan Africa in the mid-1980s.

These figures also underscore the dynamism of the nonruminant livestock sector. In the past two decades, TFP growth rates in China have been extremely high, with South Asia and Latin America not far behind. If this catching-up process continues in the next two decades, productivity in many parts of the world will reach to that level in the industrialized countries. Of course, not all the TFP projections are positive. With the exception of nonruminants, East and Southeast Asian TFP falls over the projections period. The Middle East and North Africa—a region with very high population growth rates—shows little sign of increasing TFP in agriculture. And finally, given its potential for continued high rates of population growth, as well as its low level of current productivity, the relatively slow growth rate in agriculture TFP in sub-Saharan Africa is also troubling. Without significant investments in research and extension infrastructure, it is unlikely that this trend can be reversed.

8. Summary and implications for forecasting agricultural growth and input use

Estimation of future food supply relies heavily on projections of future productivity growth in agriculture. The rate of productivity growth in agriculture is fundamental to forecasting global commodity markets, future patterns of international trade, and changes in land use. However, most current forecasts rely on PFP projections such as yield and output per head of livestock and are potentially inaccurate.

The contribution of this article to the productivity measurement literature is that it provides TFP growth measures for crops, ruminants, and nonruminants, on a global basis, for the period 1961–2001. Additionally, it tests for convergence in technical efficiency and forecasts productivity growth of these three agricultural subsectors to the year 2040. These productivity forecasts are based on our analysis of historical productivity estimates and account for technological diffusion across regions based on the convergence results.

The results indicate that developed countries have had greater historical productivity growth in crops and ruminant production than developing countries. However, developing regions show a much larger productivity growth rate in nonruminant (pigs and poultry) production. The results indicate a degree of convergence between developing and developed countries in crops and nonruminant production, but not so for ruminant production where there is evidence of technological divergence between developed and developing countries.

Our forecasts point to higher TFP growth in livestock in the developing world, while TFP growth in crops in the industrialized countries would exceed that for ruminants. The faster livestock TFP growth in developing countries is a positive development for consumers, given the relatively high income elasticities of demand for livestock products in the developing world. These future productivity growth rates also have important implications for land use, where more intensive use without additional inputs could further degrade productivity. However, to evaluate these impacts, one needs an explicit simulation model because an expanding livestock sector could also increase the demand for feedstuffs. Future research should incorporate these TFP estimates into a dynamic global trade model in order to evaluate the impacts of such growth on international trade, land use, employment, and poverty.

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Appendix A. Production value weights used to aggregate TFP growth rates

Region	Share of each sector by region (2001)			
	Crops	Ruminants	Nonruminants	Agriculture
Industrialized countries	22.6	41.2	33.6	28.4
Economies in transition	8.0	12.1	6.8	8.6
China	23.0	7.7	38.3	22.5
East and Southeast Asia	8.9	1.5	5.3	6.8
South Asia	14.8	13.4	2.3	12.3
Middle East and North Africa	4.8	4.5	2.1	4.3
Sub-Saharan Africa	6.2	5.0	1.7	5.2
Latin America and Caribbean	11.7	14.5	9.8	11.9
Total	100	100	100	100

Region	Share in agriculture (2001)			
	Crops	Ruminants	Nonruminants	Total
World	62	21	18	100
Industrialized countries	49	30	21	100
Economies in transition	57	29	14	100
China	63	7	30	100
East and Southeast Asia	82	5	14	100
South Asia	74	23	3	100
Middle East and North Africa	69	22	9	100
Sub-Saharan Africa	74	20	6	100
Latin America and Caribbean	60	25	15	100

Appendix B. Logistic function parameters for crops efficiency levels

Region	Coeff.	Estimate	St. error	*t*-value	Pr > |*t*|	R^2	Most recent structural change
Industrialized countries	α	−6.36710	1.1442	−5.5646	0.0014	0.85	1993
	β	0.11044	0.0167	6.6154	0.0006		
Economies in transition	α	−4.55573	1.3452	−3.3868	0.0117	0.62	1992
	β	0.06779	0.0201	3.379	0.0118		
China	α	−4.31135	0.4041	−10.6680	<0.0001	0.94	1988
	β	0.08171	0.0066	12.3556	<0.0001		
East and Southeast Asia	α	1.32283	0.0613	21.5686	<0.0001	0.92	1976
	β	−0.02269	0.0014	−16.1303	<0.0001		
Asia developing	α	−1.24442	0.1196	−10.4027	<0.0001	0.83	1982
	β	0.02053	0.0023	8.9738	<0.0001		
Middle East and North Africa	α	−0.83925	0.1422	−5.9031	<0.0001	0.52	1982
	β	0.01155	0.0027	4.2478	0.0005		
Sub-Saharan Africa	α	−1.89824	0.1104	−17.1910	<0.0001	0.94	1985
	β	0.02840	0.0019	14.5778	<0.0001		
Latin America and Caribbean	α	0.71592	0.1387	5.1602	0.0001	0.56	1984
	β	−0.01106	0.0025	−4.4008	0.0005		

Appendix C. Logistic function parameters for ruminants efficiency levels

Region	Coeff.	Estimate	St. error	*t*-value	Pr > |*t*|	R^2	Most recent structural change
Industrialized countries	α	2.40890	0.1545	15.5871	<0.0001	0.76	1981
	β	−0.02303	0.0030	−7.5738	<0.0001		
Economies in transition	α	0.89121	0.4332	2.0573	0.0544	0.16	1981
	β	0.01513	0.0085	1.7751	0.0928		
China	α	−7.42567	0.2507	−29.6145	<0.0001	0.97	1985
	β	0.11185	0.0044	25.866	<0.0001		
East and Southeast Asia	α	−0.16841	0.0565	−2.9815	0.0063	0.95	1974
	β	−0.02728	0.0014	−19.6788	<0.0001		
Asia developing	α	−2.28252	0.0669	−34.1222	<0.0001	0.95	1981
	β	0.02616	0.0013	19.8755	<0.0001		
Middle East and North Africa	α	1.16008	0.0493	23.5084	<0.0001	0.96	1974
	β	−0.02822	0.0012	−23.3071	<0.0001		
Sub-Saharan Africa	α	−0.71651	0.0456	−15.7023	<0.0001	0.47	1976
	β	0.00466	0.001	4.4537	0.0002		
Latin America and Caribbean	α	−1.26845	0.1501	−8.4526	<0.0001	0.83	1984
	β	0.02339	0.0027	8.6063	<0.0001		

Appendix D. Logistic function parameters for nonruminants efficiency levels

Region	Coeff.	Estimate	St. error	*t*-value	Pr > |*t*|	R^2	Most recent structural change
Industrialized countries	α	2.07361	0.9747	2.1274	0.0568	0.26	1988
	β	−0.03160	0.0159	−1.9812	0.0731		
Economies in transition	α	−2.95387	0.7176	−4.1165	0.0034	0.54	1991
	β	0.03264	0.0109	2.9822	0.0175		
China	α	−4.99659	0.6692	−7.4666	0.0001	0.83	1992
	β	0.05719	0.0100	5.7299	0.0007		
East and Southeast Asia	α	−2.16873	0.2003	−10.8273	<0.0001	0.82	1993
	β	0.01555	0.0029	5.3219	0.0018		
Asia developing	α	−2.49062	0.7195	−3.4614	0.0086	0.35	1991
	β	0.02238	0.0110	2.0392	0.0758		
Middle East and North Africa	α	1.48194	0.2035	7.2824	<0.0001	0.91	1989
	β	−0.03367	0.0033	−10.3561	<0.0001		
Sub-Saharan Africa	α	0.26364	0.5515	0.478	0.6454	0.34	1991
	β	−0.01671	0.0084	−1.9868	0.0822		
Latin America and Caribbean	α	−4.52250	0.5332	−8.4824	<0.0001	0.88	1992
	β	0.05376	0.0080	6.7606	0.0003		

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