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The Green Revolution and the productivity paradox: evidence from the Indian Punjab

Rinku Murgai

Development Research Group, The World Bank, 1818 H Street, N.W., Washington, DC 20433, USA

Abstract

Contrary to a widespread belief, total factor productivity (TFP) growth, as measured by the conventional growth accounting approach, contributed little to economic growth during the Green Revolution in the Indian Punjab. This paper shows that this ‘productivity paradox’ arises because of a fundamental problem with conventional measures of TFP growth. When technical change is not Hicks-neutral, it is impossible to separate the contribution of technical change from that of factor accumulation. Simple exercises to assess the magnitudes involved in the Punjab case show that the bias in conventional TFP estimates is severe: ‘corrected’ measures of productivity growth are between 100 and 200% higher per year during the Green Revolution. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Green Revolution of the mid-1960s led to a dramatic increase in agricultural production and radically transformed the course of Indian agriculture. Within India, the state of Punjab has been the star performer. It was the first state to widely adopt the modern high-yielding varieties (HYVs) of wheat and rice, and has been the most widely cited Indian success story of the Green Revolution. From 1966 to 1974, production of wheat, the primary winter crop, increased at an annual rate in excess of 9%. Rice, which was not widely grown prior to the Green Revolution, grew at a remarkable rate of 18% during this period. Overall, agricultural production increased at a rate of 6%.

This record of growth in production has led many economists to believe that productivity growth must have also been high in Punjab’s agricultural sector.

More recently, in the years following the Green Revolution, there has been growing concern that high rates of productivity growth have not been sustained in the light of heavy water and fertiliser inputs, diminishing growth in the yields of the major crops, and degradation of the water and land resource base.

However, the empirical evidence of productivity growth, as measured by the conventional growth accounting methods, goes directly contrary to expectations. Productivity growth in Punjab was lowest during the Green Revolution years, even as farmers switched from traditional varieties of wheat and rice to hybrid seed varieties and the agricultural sector experienced stellar growth rates in production. Productivity growth increased during a phase of rapid factor accumulation that immediately followed, after adoption of HYVs was essentially complete. This is the puzzle — “why are trends in productivity growth exactly opposite to our expectations?”

E-mail address: rmurgai@worldbank.org (R. Murgai).

Table 1
Conventional estimates of productivity growth, 1961–1994

	Entire period, 1961–1994	Green Revolution, 1966–1974	Input intensification, 1975–1985	Post-Green Revolution, 1986–1994
I. Conventional TFP growth (% per year)				
TFP	1.9	1.3	1.8	1.5
Output	5.0	5.9	4.3	4.5
Input	3.0	4.6	2.4	3.0
II. Contribution of TFP to output growth (%)				
	38.8	22.3	43.0	33.5

This paper shows that the ‘productivity paradox’ arises because of a fundamental problem with the widely used measure of total factor productivity (TFP) growth.¹ TFP is calculated by subtracting the share-weighted growth in factor inputs from the growth rate in output, so that the residual is attributed to technical progress. However, when technical change is not Hicks-neutral, the shares of payments to each factor depend on the rate and bias of technical change. As a result, the contribution of technical change is misattributed to factor accumulation and the derived residual of productivity growth is biased.

Simple exercises to assess the magnitudes involved in the Punjab case show that the bias in conventional TFP estimates is severe; ‘corrected’ measures of productivity growth are between 100 and 200% higher per year during the Green Revolution. This error has been neglected in the current literature, but is potentially extremely serious in many other regions and sectors that have undergone rapid factor accumulation amidst factor-biased technological change. Considering the widespread importance placed on measures of productivity growth to monitor the aggregate performance and sustainability of agricultural systems, it is critical that such correction procedures be used to assess and improve the accuracy of TFP estimates.

¹ The term ‘productivity paradox’ is borrowed from the literature that seeks to explain the sudden decline in productivity growth in industrialised countries after 1973, even though there were significant technological advances in some fields. Diewert et al. (1999) provide a summary of recent research on the productivity slowdown in the service sectors of industrialised countries.

2. Conventional estimates of productivity growth

There are several measures of TFP that use different rules for aggregating outputs and inputs. The method commonly used to minimise the impact of relative price changes when forming the aggregate quantity indices is a Divisia indexing procedure (Alston et al., 1995). Among alternative discrete approximations to the Divisia index, the chain-linked Tornqvist–Theil TFP index is often preferred, since it is exact for the linear homogenous translog production function (Diewert, 1976). TFP is obtained by taking the difference between the growth rates of the aggregate output and input indices.

$$\begin{aligned}
 \text{TFP} &\approx \ln \left(\frac{\text{TFP}_t}{\text{TFP}_{t-1}} \right) = \ln \left(\frac{QI_t}{QI_{t-1}} \right) - \ln \left(\frac{XI_t}{XI_{t-1}} \right) \\
 &= \sum_i \frac{1}{2} (R_{it} + R_{it-1}) \ln \left(\frac{Q_{it}}{Q_{it-1}} \right) \\
 &\quad - \sum_j \frac{1}{2} (S_{jt} + S_{jt-1}) \ln \left(\frac{X_{jt}}{X_{jt-1}} \right) \quad (1)
 \end{aligned}$$

where QI_t is the Divisia output index, XI_t the Divisia input index, and R_{it} and S_{jt} are the revenue shares of output i , and the cost share of input j , at time t , respectively.

For the purposes of computing TFP, annual data on all inputs, outputs and prices were collected at the district level during the period 1961–1994.² Major

² Considerable resources were invested to collect data (from the Indian Directorate of Economics and Statistics and various secondary sources) on individual crop and livestock products, inputs and prices at the district-level. This exercise resulted in a more comprehensive data-set than has been previously used in the Indian context. For a detailed discussion of the aggregation and valuing methods, see Murgai (1997).

farm outputs — 20 crops, fruits and livestock products — were aggregated into a Divisia output index using district-specific farm harvest prices for the crops and state-level prices for livestock and fruits. The input categories included land, labour, water, machinery, draught animals, fertilisers and pesticides. To minimise the aggregation bias, inputs of different qualities were valued by the price of each input-quality type. Land was divided into irrigated and unirrigated land, labour was disaggregated into skilled and unskilled labour based on the rural literacy rate in each district, water was divided into canal and tubewell water, and fertiliser into individual nutrient sources — nitrogen, phosphorous and potassium.³

Growth in TFP was analysed for three periods corresponding to different phases of Green Revolution technical change (Byerlee, 1992). The Green Revolution period (1966–1974) corresponds to the widespread adoption of input-responsive modern varieties of wheat and rice, which led to a dramatic increase in production. This was followed by an input intensification period (1975–1985) when the use of fertilisers and capital inputs increased rapidly, and a post-Green Revolution period (1986–1994) when input use levelled off.

Table 1 reports the estimates of the Tornqvist–Theil index of TFP growth. Punjab sustained productivity

growth rates of 1.3% or more in each period, averaging 1.9% from 1961 to 1994.⁴ These estimates are comparable to the long-term productivity growth estimates reported for Punjab and at the higher end of those reported for India as a whole.⁵ The productivity gains explain approximately 39% of the 5% growth rate in aggregate output from 1961 to 1994.

Comparing performance across periods, we see that the Green Revolution was indeed a period of extraordinary agricultural performance. Output growth was most rapid during that period, at nearly 6% per year. Paradoxically, however, productivity performance was the lowest during the Green Revolution; only 22% of the growth in output was explained by TFP growth.

In the following section, we present evidence on the trends in factor accumulation versus factor shares over the sample period. This evidence, combined with a closer look at the assumptions underlying the TFP calculations, casts doubt on the validity of conventional growth accounting estimates in the Punjab context.

3. Explaining the productivity paradox

3.1. Are conventional TFP estimates biased?

According to the TFP estimates reported in Table 1, more than three-quarters of the rate of growth in agricultural output during the Green Revolution was explained by factor accumulation. Much of this factor accumulation was in the form of rapid investment in tubewells for accessing groundwater for irrigation, tractors for land preparation, and increased use of pesticides and fertilisers. By contrast, overall labour utilisation declined (rapidly in the case of draught animals, but less so in the case of human labour since

³ As far as possible, the prices used to value inputs and outputs were those faced by the producers. That is, all taxes on the value of output were removed but all subsidies and taxes on the factors of production were retained (see Young, 1995 for discussion). For example, the fertiliser was valued at the subsidised price paid by the producers. However, using the price paid by producers to compute the factor shares is problematic in the case of inputs that are effectively rationed. In the case of canal water (a subsidised but rationed input), the price does not reflect the true shadow value paid by producers. Consequently, canal water's factor share, when computed at the levied charges, likely understates its true factor share and biases our TFP estimates. The extent of bias depends on the rate of growth of canal water use relative to other inputs and on the share of canal water in factor payments. Simulations suggest that underestimation of the shadow price biases our TFP estimates, but that the degree of bias is small since canal water use grew at a much slower rate than other relatively high priced inputs. Underestimation of the shadow price of groundwater (which may arise due to electricity shortages in the case of producers who rely upon water purchased from electric tubewells) would bias our estimates upwards. Evidence from simulations suggests that the bias is unlikely to be severe. For example, a 40% increase in the hourly price of water from electric tubewells would lower annual TFP growth rates from 1.9 to 1.8%.

⁴ To minimise the impact of end-points on the period-specific growth rates, all growth rates reported in the paper are computed by using a spline function with semi-log regressions. Growth rates for the 1961–1965 period are not reported since it is too short.

⁵ See, for example, Evenson et al. (1999), Rosegrant and Evenson (1993), Desai (1994), Kumar and Rosegrant (1994), Sidhu and Byerlee (1992), Dholakia and Dholakia (1993). Ahluwalia (1996) and Pingali and Heisey (1999) provide summaries of TFP estimates for Indian agriculture.

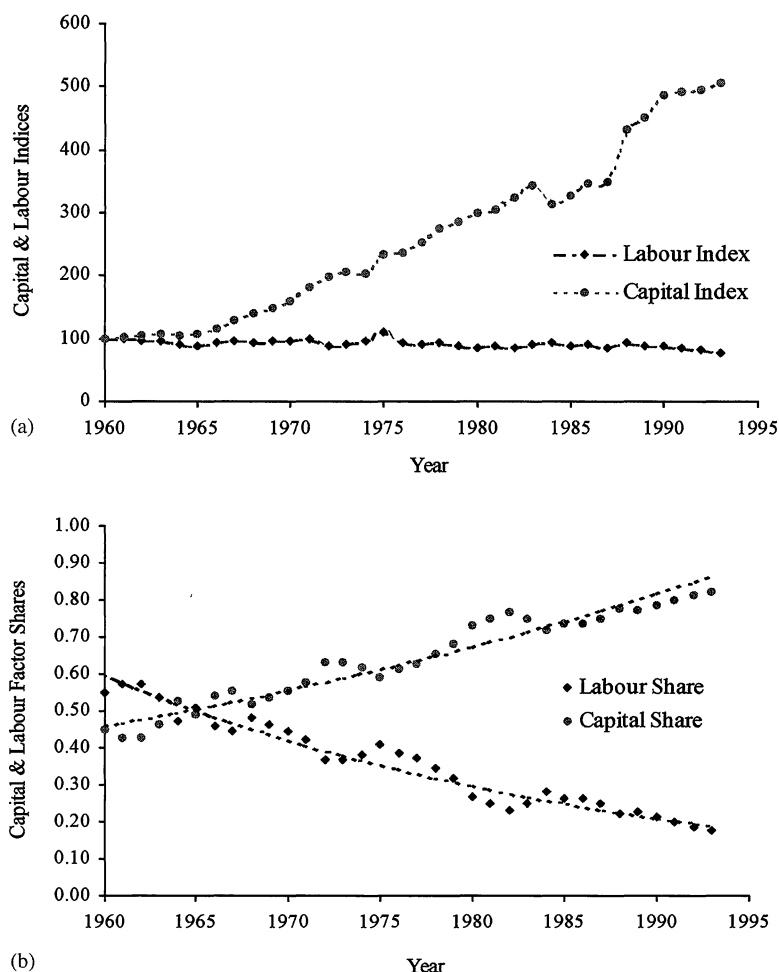


Fig. 1. (a) Evolution of weighted capital and labour indices, 1961–1994 and (b) evolution of capital and labour factor shares, 1961–1994.

utilisation rates fell but the labour force grew).⁶ The contrasting patterns of factor accumulation are starkly evident in a comparison of the patterns of evolution of weighted capital and labour indices over the sample period (Fig. 1a).⁷

⁶ Hazell and Ramaswamy (1991) found a similar decrease in the labour utilisation rates in a study of the effects of the Green Revolution in South India. They attribute the change to increased mechanisation of irrigation and paddy threshing.

⁷ All non-labour inputs (including machinery, water, land and fertiliser) are aggregated into a capital index, while human and animal labour inputs are aggregated into a labour index.

These patterns of input use are consistent with the differences in relative price movements. Since the beginning of the Green Revolution, the prices of capital inputs and fertilisers declined largely due to government subsidies, while there was a modest increase in real wages.⁸ However, there was a rather surprising pattern in the movement of factor shares over the same time period (Fig. 1b). With rapid capital accumulation and a decrease in the relative price of capital, it seems reasonable to expect a decrease in the share of factor payments that accrue to capital.

⁸ For a more detailed discussion of the trends in input and output use and prices, see Murgai (1997).

Instead, capital accumulation was accompanied by an increase, not decrease, in its share in total factor payments.

There are two contending explanations for the increase in the capital share despite tremendous capital-deepening. First, the underlying production function for the Green Revolution technologies had an elasticity of substitution between capital and labour that was high enough to compensate for the reduction in the marginal productivity of the capital. Alternatively, there was labour-saving technical change which led to an increase in the relative return to capital and therefore an increase in the share of capital. While we cannot be sure which explanation is true, there are strong reasons to believe the latter.

We know from other empirical sources (Kako, 1978; Hayami and Ruttan, 1985; Thirtle, 1985a,b) that the elasticity of substitution between capital and labour inputs is typically close to one (and usually smaller than one) which is too low to explain the increase in capital's share.⁹ Moreover, the changes in factor proportions during the Green Revolution were so large that it is highly implausible that these changes represent pure substitution effects along a fixed production function with constant technology.

We also have ample evidence that the seed improvements that spearheaded the Green Revolution were directed towards the selection of more fertiliser and water-responsive varieties. The traditional varieties had equal or higher yields than the improved varieties at lower levels of fertilisation and irrigation, but they did not respond to higher applications of these inputs (Hayami and Ruttan, 1985). It is likely, therefore, that the increase in capital's share reflects the development of crop varieties that were biased toward water and fertiliser use.¹⁰

⁹ If ordinary factor substitution in response to relative price movements was the only reason underlying changes in the factor share, the observed capital share changes would imply an elasticity of substitution close to 7, if the underlying production function were a scale-neutral CES.

¹⁰ Indeed, the extent to which the factor shares would have changed in the absence of relative price changes is precisely how the degree of biased technological change has been measured in the literature (Binswanger, 1974, 1978; Yeung and Roe, 1978; Hayami and Ruttan, 1985).

Since capital is the more rapidly growing input and its share is higher than it would have been in the absence of technical change, the aggregate input growth is over-estimated (see Eq. (1)). As a result, the TFP residual under-estimates true productivity growth. The next sub-section spells out this argument in greater detail.

3.2. Non-identifiability of factor accumulation and technical progress

Although distinguishing factor-biased technical change from the price-induced substitution effects has been the focus of a significant fraction of the agricultural production economics literature (see Alston et al., 1995), the implications of biased technical change for index number approaches to productivity measurement have been neglected.

The basic issues are most easily demonstrated in a two-factor case. Consider a production function with two inputs, capital (K) and labour (L),

$$Q_t = A_t f(E_{Kt}K_t, E_{Lt}L_t) \quad (2)$$

where A is the coefficient of Hicks-neutral technical change, E_K and E_L are the coefficients of capital-saving and labour-saving technical change, and the production function (f) is linear homogenous and well-behaved. Rewriting Eq. (1) for this simple production function, conventional productivity growth is measured as the residual growth in output, after subtracting the weighted growth in inputs K and L ,

$$\ln \left(\frac{TFP_t}{TFP_{t-1}} \right) = \ln \left(\frac{Q_t}{Q_{t-1}} \right) - \bar{\alpha} \ln \left(\frac{K_t}{K_{t-1}} \right) - (1 - \bar{\alpha}) \ln \left(\frac{L_t}{L_{t-1}} \right) \quad (3)$$

where $\bar{\alpha}$ is the average share of capital in factor payments between period $t-1$ and t . Notice that the rates of growth of the two inputs are weighted by their observed factor shares.

If factors are paid their marginal products, the growth rate of the share of factor payments to capital in total output is

$$\hat{\alpha} = \left(\frac{1 - \sigma}{\sigma} \right) (1 - \alpha_{t-1}) [(\hat{E}_L - \hat{E}_K) - (\hat{K} - \hat{L})] \quad (4)$$

where the hat symbol ($\hat{\cdot}$) denotes the growth rate, α the share of capital in factor payments and σ the elasticity of substitution between capital and labour. As Eq. (4) shows, the evolution of factor shares depends on (1) the form of the production function, as encapsulated by σ , (2) the effect of factor-substitution along a fixed-technology isoquant in response to the changes in relative factor prices and (3) the effect of biased technical change.¹¹ Factor shares are independent of technical change only if the elasticity of substitution between the inputs is unity ($\sigma = 1$) or if the technical change is Hicks-neutral ($\hat{E}_L - \hat{E}_K = 0$).¹² When it is relatively difficult to substitute capital for labour ($\sigma < 1$), an increase in the capital:labour ratio ($(\hat{K} - \hat{L}) > 0$), would lead to a decrease in the share of factor payments to capital. However, if there is labour-augmenting technical change ($\hat{E}_L > \hat{E}_K$), the relative return of capital increases.

Consider the case of the Green Revolution. The increase in capital's share despite capital deepening could be either because of σ that is much greater than 1 (as noted in footnote 9) or because of labour-saving technical change. In the latter case, since capital is the more rapidly growing input and its weight in the Divisia input index is higher than it would be in the absence of technical change, too much of the output growth is attributed to factor accumulation, and too little to the residual (i.e. TFP growth).¹³

¹¹ For a non-homothetic production function, factor shares also depend on the scale of production since the expansion path is non-linear (Antle and Capalbo, 1988; Alston et al., 1995). In this paper, we focus on the homothetic case, since empirical evidence on Green Revolution technologies suggests that the underlying production function is linear homogenous and therefore, homothetic (Ruttan and Binswanger, 1978; Hazell and Ramaswamy, 1991).

¹² For the formulation of the decomposition of factor shares into substitution and biased technical change effects based on the cost function (dual) approach, see Binswanger (1974) and Hayami and Ruttan (1985). Rodrik (1997) uses the primal decomposition approach to make the same argument about the difficulty of measuring biased technical change in the context of the east Asian economies.

¹³ In practice, any chain-linked Divisia index (not just the Tornqvist–Theil index) that uses observed factor shares to aggregate inputs suffers from this problem. Mathematically, the bias arises because of the path-dependent properties of the Divisia index as a line integral (Hsieh, 1998). The TFP index is not path dependent only if technological change is Hicks-neutral.

3.3. Bias-corrected measures of productivity growth

How can we correct conventional TFP estimates? In order to separately identify the contribution of factor accumulation from that of technical change, we need to estimate what factor shares would have been in the absence of a technical change. The task is to sort out to what extent the share changes have been due to biased technical change and to what extent to price changes.

However, we need to contend with a fundamental identification problem, related to the Diamond et al. (1978) 'non-identification theorem' which shows that given the actual observations on input change and factor shares, it is impossible to separately identify the parameters of the underlying production function from the bias of technological change.¹⁴ As a result, it is impossible to isolate the contribution of technological change from that of factor accumulation, without making assumptions about the underlying production function.

Given this identification problem, we cannot correct TFP estimates without knowing the 'true' substitution parameters of the production function. However, we can improve the accuracy of the estimates by making assumptions about reasonable values of σ that are available from other empirical studies.¹⁵ Assuming a certain σ , and using initial factor shares (in year 0) and growth rates of factor deepening (between year 0 and t), the differential equation for factor share changes (Eq. (4)) can be solved to estimate what factor shares at time t would have been in the absence of

¹⁴ Stated differently, given time series data for a single economy with a classical aggregate production function, one finds that the same time series could have been generated by an alternative production function having an arbitrary σ or bias at the observed points. In addition, if the underlying production function were non-homothetic, it may be possible to assign an arbitrary elasticity of substitution and the bias of technical change, and explain the observed time series solely in terms of scale bias.

¹⁵ We cannot estimate σ using our data because of the small number of cross-sectional units (districts) in our sample. The parameters of the production function must be estimated with cross-section, rather than time-series data, since the effects of biased technical change are incorporated in the observed evolution of factor shares (Binswanger, 1978; Diamond et al., 1978). The difficulty with cross-sectional estimation, of course, is that all units should be on the same production function (i.e. there is no unobserved heterogeneity).

Table 2
Conventional vs. corrected estimates of TFP growth (two-factor CES)

	Entire period, 1961–1994	Green Revolution, 1966–1974	Input intensification, 1975–1985	Post-Green Revolution, 1986–1994
I. Conventional TFP growth (% per year)				
TFP	1.9	1.3	1.8	1.5
II. Corrected TFP growth (% per year)				
$\sigma = 0.3$	4.8	4.0	2.9	2.2
$\sigma = 0.7$	3.7	3.0	2.6	1.2
$\sigma = 1.3$	2.9	2.7	2.5	0.9
III. Bias in TFP (= II – I)				
$\sigma = 0.3$	2.9	2.7	1.1	0.7
$\sigma = 0.7$	1.7	1.7	0.8	–0.3
$\sigma = 1.3$	1.0	1.4	0.7	–0.6

biased technical change.¹⁶ The Divisia input index is then computed using the corrected factor shares, and the residual growth in output gives us a measure of bias-corrected productivity growth.¹⁷

Table 2 reports bias-corrected estimates of TFP for three different values of σ in a two-factor scale-neutral CES production function.¹⁸ For the ease of comparison, the first row in the table reproduces the conventional TFP estimates from Table 1. There are several points of note. First, the bias in conventional TFP estimates is extremely high. Comparing the first and second panels, the conventional TFP estimates under-estimate true productivity growth by 1–3% per year. Putting it differently, depending on the choice of σ , the bias-corrected TFP estimates are more than double the conventional estimates, per year. Second, the bias is greater for lower elasticities of substitu-

tion. Clearly, the lower our priors about the substitutability between factors, greater we must assume the under-estimation in conventional productivity estimates to have been. Third, the under-estimation in conventional TFP estimates is the greatest during the Green Revolution period. This is expectedly because the shift from traditional varieties to modern HYVs was much more drastic in terms of the technological bias than the later shifts from the original Green Revolution varieties to further improved varieties. Finally, comparing the corrected TFP estimates across the periods (and contrary to the trends in conventional estimates), there is a clear decline in TFP growth after the Green Revolution, regardless of the assumptions about the elasticity. For example, when the elasticity of substitution is 0.7, TFP growth declines from 3% per year during the Green Revolution to 1.2% in the post-Green Revolution period. These estimates confirm suspicions about the declining productivity of irrigated agricultural systems that are typical of South Asia.¹⁹

The under-estimation in conventional TFP is robust to other specifications of the production function. We repeated the exercise for a multi-factor CES production function, with land and labour as the two primary factors of production, and capital goods decomposed into those that substitute for land and those that substitute for labour (Hayami

¹⁶ This correction procedure is analogous to the approach that has been used to measure the degree of biased technical change (Binswanger, 1974; Hayami and Ruttan, 1985). The approach has been to (1) measure the elasticity of substitution using cross-sectional data and (2) based on these parameters, measure the extent to which the factor shares would have changed had the factor prices remained constant. This approach, although the authors do not state it explicitly, also circumvents the identification problem by making reasonable assumptions about the value of σ in the underlying production function.

¹⁷ The solution for the factor share differential equation and the bias-corrected Divisia input index is provided in Appendix A.

¹⁸ As in Fig. 1a and b, the two factors are 'capital', which is a weighted index of all non-labour inputs, and 'labour', which is a weighted index of human and animal labour. For a detailed discussion of aggregating different input types into a single index, see Young (1995).

¹⁹ Murgai et al. (2000) relate the decline in the productivity of irrigated agriculture in the Indian and Pakistan Punjab to resource degradation, especially in the rice–wheat cropping system.

Table 3
Corrected estimates of TFP growth, 1961–1994 (multi-factor CES)^a

	$\sigma = 0.2$	$\sigma = 0.5$	$\sigma = 0.9$
Average annual TFP growth (%)			
$\sigma_A = \sigma_L = 0.2$	5.07	4.98	4.94
$\sigma_A = \sigma_L = 0.7$	4.99	4.87	4.84
$\sigma_A = 0.8; \sigma_L = 0.7$	4.98	4.85	4.81
$\sigma_A = 0.7; \sigma_L = 0.8$	4.97	4.86	4.82

^a Note: σ_A is the elasticity of substitution between labour and labour-saving inputs (machines), σ_L the elasticity of substitution between land and land-saving inputs (fertiliser and water) and σ the elasticity of substitution between land and labour aggregates.

and Ruttan, 1985). Land-saving capital is identified with biological, chemical and water control investments, while the labour-saving capital consists of machinery, particularly tractors. Technical change is classified as land-saving or labour-saving according to whether it increases the productivity of the land-saving or the labour-saving capital goods. Table 3 reports the bias-corrected TFP growth rates for the period 1961–1994. For all reasonable values of the elasticities of substitution, the estimated growth rate of TFP lies between 4 and 5% per year.²⁰ For these values, the conventional TFP estimate of 1.9% per year, therefore, under-estimates the contribution of technical progress by approximately 2% per year.

4. Conclusions

India's Punjab exemplifies the Green Revolution of the mid-1960s, when it achieved dramatically high rates of growth in agricultural output. Growth during the Green Revolution can be attributed largely to improvements in the yields of wheat and rice and to the expansion of area under wheat and rice HYVs.

²⁰ The elasticities used for the simulations in this paper are the ones reported by de Janvry et al. (1989) as the average of those reported by several empirical studies. From a survey of various empirical estimates of the Allen partial elasticities of substitution between the inputs in the same sub-function and between the inputs in different sub-functions, de Janvry et al. (1989) report that elasticities within sub-functions are higher than elasticities across the sub-functions and that they are all systematically lower than unity.

However, most yield improvements resulted from rapid factor accumulation, especially in fertilisers and capital inputs. Contrary to a widespread belief, productivity growth, as measured by the conventional growth accounting approach, contributed little to the economic growth.

A discussion of the conventional method of growth accounting helps to explain why measured productivity growth was much lower than expected. When technical change is not Hicks-neutral, it is impossible to separate the contribution of technical change from that of factor accumulation. The difficulty arises because when technical change is biased, the share of payments to each factor depend on the rate and bias of the technical change. As a result, when observed factor shares are used to compute an aggregate Divisia input index, part of the effects of technical change are captured in the index of factor accumulation.

In the case of the Indian Punjab, the bias in conventional TFP estimates is severe. Conventional estimates of TFP growth are biased downward during the Green Revolution because some of the contribution of labour and land-saving technical change is attributed to factor accumulation. Corrected TFP estimates also show that, contrary to the trends observed in the conventional estimates, there has been a marked decline in the productivity since the Green Revolution, raising concerns about the sustainability of irrigated agricultural systems.

More generally, in this paper, we have used the Tornqvist–Theil index as an example to illustrate the problem with conventional growth accounting in the presence of biased technical change. In practice, any chain-linked Divisia index that uses observed factor shares to aggregate the inputs needs to be corrected if there is a likelihood that technical change has been biased towards one or more factors. Indeed, if we believe in the role of induced innovation in maintaining the productivity growth, we should start incorporating its impact into our measures of productivity growth.

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Appendix A. Correcting factor shares and factor accumulation for technical change bias

A.1. Corrections for a two-factor CES production function

A scale-neutral CES production function with two inputs, capital (K) and labour (L) can be written as

$$Q = [\gamma(E_L L)^{(\sigma-1)/\sigma} + (1-\gamma)(E_K K)^{(\sigma-1)/\sigma}]^{\sigma/(1-\sigma)} \quad (\text{A.1})$$

where E_K and E_L are the coefficients of capital-saving and labour-saving technical change, γ is a distribution parameter between 0 and 1, and σ the elasticity of substitution between capital and labour. Under profit maximization (when factors are paid their marginal products), the rate of growth of the share of capital in factor payments is given by Eq. (4) (see Section 3.2).

Given the initial factor share for capital observed at time 0 (1961), by solving the differential Eq. (4), the factor shares that would have been observed in the time period T (1994) in the absence of Hicks-biased technical change can be computed as

$$\alpha_T = \frac{\alpha_0 \exp[(\sigma-1)/\sigma](\hat{K} - \hat{L})T}{1 - \alpha_0 + \alpha_0 \exp[(\sigma-1)/\sigma](\hat{K} - \hat{L})T} \quad (\text{A.2})$$

The bias-corrected Divisia input index, using the corrected factor shares is then given by

$$\hat{I} = \hat{K} + \frac{[\sigma/(1-\sigma)] \ln(\alpha_T/\alpha_0)}{T} \quad (\text{A.3})$$

TFP growth is computed by subtracting the bias-corrected growth rate of aggregate inputs (Eq. (A.3)) from the observed growth rate of aggregate output. The sensitivity of the corrected TFP growth rate to different assumptions about σ depends on the growth rate of the capital:labour ratio and on the initial shares of capital and labour in total income.

A.2. Corrections for a multi-factor CES production function

A multi-factor production function that makes a distinction between labour, land, labour-saving and land-saving factors can be represented as

$$\begin{aligned} Q &= [(X_A)^{(\sigma-1)/\sigma} + (1-\gamma)(X_L)^{(\sigma-1)/\sigma}]^{\sigma/(1-\sigma)}, \\ X_A &= [\delta(E_A A)^{(\sigma_A-1)/\sigma_A} \\ &\quad + (1-\delta)(E_F F)^{(\sigma_A-1)/\sigma_A}]^{\sigma_A/(1-\sigma_A)}, \\ X_L &= [\beta(E_L L)^{(\sigma_L-1)/\sigma_L} \\ &\quad + (1-\beta)(E_M M)^{(\sigma_L-1)/\sigma_L}]^{\sigma_L/(1-\sigma_L)} \end{aligned} \quad (\text{A.4})$$

where $X_A(\cdot)$ is the 'land' input index, $X_L(\cdot)$ the 'labour' input index, A and L are land and labour use, respectively, F the land-saving capital (fertiliser), M the labour-saving capital (machinery), and the E_i s are indices of biased technical change (see Hayami and Rutan (1985) for a discussion of the advantages of the two-level CES function over the translog function in the context of characterising biased technical change in agriculture). When factors are paid their marginal products, the rate of growth of factor shares is given by

$$\begin{aligned} \hat{\alpha}_F - \hat{\alpha}_{A'} &= \left(\frac{\sigma_A - 1}{\sigma_A} \right) \left(1 - \frac{\alpha_F}{\alpha_{A'}} \right) \\ &\quad \times [(\hat{F} - \hat{A}) - (\hat{E}_A - \hat{E}_F)] \quad \text{and} \\ \hat{\alpha}_M - \hat{\alpha}_{L'} &= \left(\frac{\sigma_L - 1}{\sigma_L} \right) \left(1 - \frac{\alpha_M}{\alpha_{L'}} \right) \\ &\quad \times [(\hat{M} - \hat{L}) - (\hat{E}_L - \hat{E}_M)] \end{aligned} \quad (\text{A.5})$$

where the hat symbol ($\hat{\cdot}$) denotes growth rate, α_F and α_M are the shares of land-saving and labour-saving inputs in total income. The shares of the land (X_A) and labour (X_L) aggregates in total income are given by $\alpha_{A'}$

and $\alpha_{L'}$, respectively (i.e. $\alpha_{A'} = \alpha_F + \alpha_A$ and $\alpha_{L'} = \alpha_M + \alpha_L$). As in the two-factor case, given the initial factor shares in time period 0 (1961), the factor shares (more precisely, $\alpha_F/\alpha_{A'}$ and $\alpha_M/\alpha_{L'}$) that would have been observed in time period T (1994) in the absence of Hicks-biased technical change can be computed for different values of the elasticities of substitution.

The Divisia input index using these bias-corrected factor shares is then given by

$$\hat{I} = \hat{X}_A + \frac{[\sigma/(1 - \sigma)] \ln[\alpha_{A'}(T)/\alpha_{A'}(0)]}{T} \quad (\text{A.6})$$

where

$$\hat{X}_A = \hat{F} + [\sigma_A/(1 - \sigma_A)] \ln \left[\frac{\alpha_F(T)/\alpha_{A'}(T)}{\alpha_F(0)/\alpha_{A'}(0)} \right] \quad (\text{A.7})$$

The TFP residual is computed by subtracting the bias-corrected growth rate of aggregate inputs (Eq. (A.6)) from the observed growth rate of the aggregate output. The sensitivity of the computed TFP growth rate to different assumptions about σ , σ_A , and σ_L depends on the growth rate of the fertiliser:land ratio and machines:labour ratio, and the initial shares of fertiliser and land in the total income.

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