TECHNOLOGICAL CHANGE AND THE PRODUCTIVITY SLOWDOWN IN FIELD CROPS: UNITED STATES, 1939-78

Colin G. Thirtle

Abstract

In the past four decades, productivity in United States field crops has been transformed by the mechanical and fertilizer revolutions. Since input data are typically not available by crop, most investigations of productivity have been at the aggregate level. This paper develops a simultaneous equation, partial adjustment model of the demand for inputs, which generates estimates of the technical change parameters for wheat, corn, soybeans, and cotton. These estimates allow comparisons of the factor saving biases in technical change, leading to a novel test of the induced innovation hypothesis and the suggestion that the productivity slowdown may yet affect agriculture in the United States.

Key words: separability, biased technical change, induced innovation, productivity slowdown.

During the past four decades, field crop production in the United States has been transformed by the "mechanical" and "fertilizer" revolutions. Since non-experimental input data are typically not available by crop (Just et al., p. 770), these major developments have usually been investigated at the aggregate output level. However, the literature suggests important historical differences between crops, both in mechanical and biological advances, that should not be sacrificed to aggregation. This study helps rectify the situation by generating technical progress parameters for wheat, corn, soybeans, and cotton. These estimates are used to construct measures of the factor-saving biases of technical change, leading to a test of the induced innovation hypothesis, based on inter-crop comparisons.

The crop-specific data, provided by the Economic Research Service, USDA, are described in the first section of the paper. In the second section, a simultaneous equation, partial adjustment model of the demand for inputs is developed. The basic empirical results generated by the model are reported and interpreted in the third section, which concentrates on inter-crop comparisons of the rates of technical change. In the fourth section, the analysis is extended to biases in technical change, returns to scale and inter-regional and inter-temporal comparisons. The results facilitate a simple but powerful test of the induced innovation hypothesis and an investigation of the "productivity slowdown" in United States field crop production. Lastly, the conclusion summarizes the results and considers the effect of forty years of biased technical change on future productivity growth.

DATA

The data for outputs, inputs, and prices are annual observations for the years 1939-78, for the ten United States' farm production regions. For each of the four crops, the forty time series observations for the ten regions were pooled to give data sets of four hundred observations. Data for outputs are in terms of physical quantities rather than values, as are the series for inputs of land (acreage harvested) and labor (total hours required). These were provided by the USDA for each crop. In a more aggregated form, these series appear in USDA (1978a), as do the machinery data provided by the USDA for the sum of the dollar values of interest, depreciation, operating expenses, and license fees for tractors, trucks, and other farm machinery and equipment, appropriately deflated and ad-

Colin G. Thirtle is a Lecturer, Department of Agricultural Economics, Faculty of Economic and Social Studies, University of Manchester, Manchester M13 9PL, England.

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justed to include workstock (the 15 million horses, mules, and oxen on United States farms at the beginning of the period were a significant addition to the 42 million tractor horsepower which was available). The machinery input for each crop, by region, was then taken to be proportional to that crop's share in the total acreage harvested.

Kaneda has argued that investigations of technical change in agriculture must include intermediate inputs such as fertilizer and other agricultural chemicals, or the productivity gains attributable to improvements in these inputs will be incorrectly attributed. The fertilizer series are price-weighted averages of the application rates for the three major nutrients (from USDA (1978b) and earlier documents), multipled by the acreages to produce total input series. The method and the imputed price weights (for N, P, & K for 1955) were taken from Griliches (1960, p. 1416). Pesticide use data were provided by the ERS, USDA, but like the machinery data, they were not crop-specific and were allocated according to acreage harvested.

Input and output prices are included among the explanatory variables in the behavioral model developed in the next section. The output prices on which farmers' production decisions were based are the futures prices at the time of planting for delivery after the harvest date (the Chicago Board of Trade and New York Cotton Exchange). The price of labor is the region-specific hourly wage rate without room and board (USDA, 1980). Region-specific land values, rather than rents, form the basis for the price of land, since rental information was not available for a portion of the period (USDA, 1979). However, the series was adjusted for the years 1973-78 using the 1973 rent-to-value ratio in order to exclude the rapid increase in land values since 1973 (the rent-to-value ratio changed dramatically over this period). Fertilizer prices are based on the price series (USDA, 1980) for a commonly used mixed fertilizer which was multiplied by the inverse of a "nutrient content" index in order to adjust for the improvement in the quality of fertilizer over the 40-year period. Region-specific price data for machinery in aggregate were not available and very few prices for a particular type of machine were reported for the entire period. An exception was wheeled tractors of 30-39 belt horsepower. Thus, this tractor price series was used to represent region-specific machinery prices (USDA, *Agricultural Statistics*). In case the tractor price series was not representative of other types of machinery, the USDA farm machinery price index (not available at the region-specific level) was used as an alternative machinery price series but this change did not significantly affect the results.

The data for land, labor, fertilizer, and machinery were collinear initially (and collinear with the time trend). Conversion of fertilizer application rates per acre to a total input measure required multiplication by the land input, which exacerbated the problem. Similarly, the machinery series was calculated proportionally to the land area. As a result, some of the correlations between variables were alarmingly high.

THE MODEL

A model is required that is both parsimonious in parameters and imposes theoretical constraints. Kaneda has argued in favor of the two-stage constant elasticity of substitution production function with separability between land/fertilizer (A,F) and labor/machinery (L,M). Separability assumptions of this type have been common in the literature. See for example Sen, Sanders and Ruttan, Kislev and Peterson and de Janvry (1977, 1978) who also considered technical change. By definition the function is separable if:

$$(1) \quad \frac{\partial\left(\frac{F_i}{F_j}\right)}{\partial X_k} = 0 \text{ for all i, j} \subset N \text{ and } k \not\subset N,$$

where, for this two group case, N denotes either group of factors, F_i, F_j are the marginal products of X_i and X_j, and X_k is a third factor not in group N. Sen (p. 280) assumed separability, arguing that,

> *we have to distinguish between two types of capital goods ... those which replace labor (e.g. tractors) and those which replace land (e.g. fertilizers) ... Broadly speaking, however, our experience seems to suggest that while investment in fertilizers, or in irrigation, or in pest control, increases yield per acre considerably (without replacing labor), investment in machinery like tractors, threshing machines etc. is useful mainly in replacing labor (without raising yield per acre).*

A two stage CES function was fitted to the data described by Thirtle (1984). However, far less sensitive estimators of the technical change parameters are obtained if the substitution elasticities are constrained, giving the nested Cobb Douglas/CES form:

$$(2)\ Q=(\theta(A^{\alpha}F^{\Phi}e^{\delta_t})^{-\rho}+\eta(L^{\lambda}M^{\mu}e^{\gamma_t})^{-\rho})^{-\frac{1}{\rho}}.$$

This function leads to a system of simultaneous linear equations for the demand for inputs (equations (4)-(7) which follow), with non-linear constraints across equations, in which the technical change parameters are independent of the substitution elasticities. The distribution parameters, θ and η, determine the output elasticities in conjunction with the factor-specific coefficients $(\alpha,\varphi,\lambda,\mu)$. ρ is the substitution parameter and Q is output.

The exponential time trends, e^{δ_t} and e^{γ_t} represent Hayami and Ruttan's yield-raising biological/chemical technical change and labor-saving mechanical technical change, respectively. These terms may be viewed as representing the (neutral) shift of the innovation possibility curves (IPCs) in later versions of the Hayami and Ruttan model (Binswanger et al.) rather than substitution along the IPCs as in the earlier model.[1] Alternatively, the technology terms may be viewed as describing shifts of conventional neoclassical isoquants, since the model presented here avoids the confusing concept of the innovation possibility curve. Viewed in this way, the parameter δ describes the shifting of the land/fertilizer isoquant toward the origin, representing increased yield per unit of inputs. This results from superior biological characteristics built into the new seed varieties and has been called biological change by Hayami and Ruttan (pp. 43-53). Similarly, the parameter γ represents the shift of the labor/machinery isoquant that results from the embodiment of improved mechanical technology in farm machinery and equipment.

The function is restrictive, imposing substitution elasticities of unity within the two input groups but since these elasticities are not central to the analysis, the restriction is unobjectionable provided it does not bias the estimates of technical change. The output elasticities, the elasticity of substitution between the input groups, and returns to scale are endogenously determined (the last since although the CES is constrained to give constant returns, the two Cobb-Douglas nests need not be).

Assuming that producers buy their inputs and sell their output in perfectly competitive markets, prices may be treated as exogenous to the individual producer. At the regional level, it is reasonable to assume that the wage is exogenously determined and that fertilizer and machinery are elastic in supply. However, the exogenous "price" of land is more difficult to defend since it is affected by agricultural productivity. Taking the objective to be profit maximization subject to the technical constraints imposed by the production function, the problem becomes:

$$(3)\ \text{Max}\ \pi = PwQ - RA - PfF - WL - PmM - \beta(Q-[\theta(A^{\alpha}F^{\Phi}e^{\delta_t})^{-\rho} + \eta(L^{\lambda}M^{\mu}e^{\gamma_t})^{-\rho}]^{-1/\rho}$$

where π is profit, R is the price of land, Pf is the price of fertilizer, W is the price of labor, Pm is the price of machinery, Pw is the price of the output, and β is the Lagrangian multiplier. Taking the logarithms of the first order conditions, including stochastic disturbances, and solving for the four inputs and mean differencing[2], the variables give the

[1]This avoids confronting the neoclassical distinction between factor substitution and technical change. In an early comment on the induced innovation hypothesis, Blaug referred to the *troublesome notion of innovations induced by changes in factor prices - this would seem to involve factor substitution, not technical change."* This problem is exacerbated in the earlier Hayami and Ruttan model since technical change is represented only by substitution along the innovation possibility curve, which Ahmad defined to be the *envelope of all the alternative isoquants (representing a given output on various production functions) which the businessman expects to develop with the use of the available amount of innovating skill and time."*

[2]After taking logarithms, the mean value was subtracted from the series for each variable, removing regional efficiency differences to the extent that they are multiplicative and thus allowing pooling of time series and cross section data. The procedure removes the intercept terms, thus simplifying estimation of the model but at the cost of φ and η not being identified.

following four equations[3] for the demand for inputs:

$$(4)\quad LnA^{*} = -[\rho\varphi/\rho\alpha+1)]LnF + [(\rho+1)/(\rho\alpha+1)]LnQ - [1/(\rho\alpha+1)]Ln(R/Pw) - [\rho\delta/\rho\alpha+1)]t + U_a$$

$$(5)\quad LnF^{*} = -[\rho\alpha/\rho\varphi+1)]LnA + [(\rho+1)/(\rho\varphi+1]LnQ - [1/(\rho\varphi+1)]Ln(Pf/Pw) - [\rho\delta/(\rho\varphi+1)]t + U_f$$

$$(6)\quad LnL^{*} = -[\rho\mu/(\rho\lambda+1)]LnM + [(\rho+1)/(\rho\lambda+1)]LnQ - [1/(\rho\lambda+1)]Ln(W/Pw) - [\rho\gamma/\rho\lambda+1)]t + U_l$$

$$(7)\quad LnM^{*} = -[\rho\lambda/(\rho\mu+1)]LnL + [(\rho+1)/(\rho\mu+1)]LnQ - [1/(\rho\mu+1)]Ln(Pm/Pw) - [\rho\gamma/\rho\mu+1)]t + U_m$$

where * indicates the desired level of the input.

This is a simple example of the general linear structural equation model (Dhrymes, Ch. 6), many properties of which are well known. It is clear that the system is over-identified, since there are sixteen simple estimated coefficients which are composed of only seven underlying production function parameters. Indeed, if constant returns are imposed on the model, then $\varphi = 1-\alpha$ and $\mu = 1-\lambda$, reducing the number of independent parameters to five. The over-identified system is non-linear in parameters. It may be estimated by non-linear two stage least squares or three stage least squares, which is asymtotically equivalent to full information maximum likelihood, and is efficient, but at the expense of being generally less robust than the two-stage method.

The model presented in equations (4)-(7) can be modified for the study of time series data, where gradual adjustment towards long-run desired levels of inputs is to be expected, with prices seldom remaining constant for long enough for these values to actually be observed. Thus A^*, F^*, L^* and M^* should be treated not as desired quantities but as long-run target levels towards which the system is adjusting. Suppose that the movement of factor X towards its longrun target value X^* can be described by the difference equation

$$(8)\quad LnX_t - LnX_{t-1} = a(LnX^{*}_t - LnX_{t-1}),$$

where the constant of proportionality, a, is what Nerlove has called the "elasticity of adjustment." Applying this partial adjustment process to the four inputs in equations (4)-(7) gives:

$$(9)\quad LnA_t + [a\rho\varphi/(\rho\alpha+1)]\,LnF_t = (1-a)LnA_{t-1} + [a(\rho+1)/(\rho\alpha+1)]LnQ_t - [a/(\rho\alpha+1)]Ln(R/Pw) - [a\rho\delta/(\rho\alpha+1)]t + U_a$$

$$(10)\quad LnF_t + [b\rho\alpha/(\rho\varphi+1)]LnA_t = (1-b)LnF_{t-1} + [b(\rho+1)/(\rho\varphi+1)]LnQ_t - (b/(\rho\varphi+1)]Ln(P_f/Pw) - (b\rho\delta/(\rho\varphi+1)]t + U_f$$

$$(11)\quad LnL_t + [c\rho\mu/(\rho\lambda+1)]LnM_t = (1\text{-}c)LnL_{t-1} + [c(\rho+1)/(\rho\lambda+1)LnQ_t - [c/(\rho\lambda+1)Ln(W/Pw) - (c\rho\gamma/(\rho\lambda+1)]t + U_l$$

$$(12)\quad LnM_t + [d\rho\lambda/(\rho\mu+1)]LnL_t = (1-d)LnM_{t-1} + [d(\rho+1)/(\rho\mu+1)]LnQ_t - (d/(\rho\mu+1)]Ln(Pm/Pw) - (d\rho\gamma/(\rho\mu+1)]t + U_m,$$

where a, b, c, and d are the adjustment elasticities. The major change is that the lagged value of each endogenous input now appears as an explanatory variable.

EMPIRICAL RESULTS

Though the model developed in the last section formed the basis for all empirical investigations that were undertaken, numerous variations remained possible. First, the existence of alternative price and input series

[3]The first order conditions include the derivative of equation (3) with respect to the Lagrangian multiplier, which should be solved with output as the endogenous variable. This equation was not log-linear and was omitted. Thus, Q appears only as an exogenous variable and was substituted for the right-hand-side of equation (2) as if the equation was non-stochastic. To avoid simultaneous equation bias problems, this requires an error-free series for Q. Assuming that the major cause of output errors is the weather, such a series was constructed by multiplying the acreage *PLANTED* by a 5-year moving average of the yield. However, the parameter estimates were not affected by this change.

was noted in the data section. In addition, attempts were made to include other inputs, especially pesticides and workstock. Second, the model can be transformed to take account of the relative importance of the different regions in the production of each crop by weighting the observations with regional shares in output or more simply by including only the regions of major importance. Third, a constant return to scale constraint may be imposed on the model, or it may be transformed by dividing the observations by the number of farms in order to consider returns to scale (see Further Issues section). Fourth, the adjustment lags need not be set at 1 year, but may be varied to determine the adjustment period; nor need the adjustment lags be independent as it is assumed in the model presented in equations (9)-(12) (Nardiri and Rosen). Finally, with 40 years of time series and ten regions, there is considerable scope for subdividing the data set to allow for inter-temporal and inter-regional comparisons (particularly, in this section, the technical change parameters are held constant for the entire period).

These possibilities were investigated and will be considered in the next section.[4] This section reports the basic results of the model with emphasis on the technical change (TC) parameters. Fortunately, the biological and mechanical TC terms (δ and γ respectively) proved to be the least sensitive estimates in the model, showing only minor variations according to the permutations of specification and data series that were used. This was especially true when the constant returns to scale constraint was imposed (probably due to greater parsimony in parameters) and, consequently, the estimates reported in Table 1 are for this version of the model.[5]

Estimates of the substitution parameter (ρ) are reported in the first column of Table 1. Since the two input groups are functionally separable, the between group direct partial elasticity of substitution is a constant,

$$\sigma = \frac{1}{1+\rho} = \sigma_{at} = \sigma_{am} = \sigma_{ft} = \sigma_{fm} ,$$

where the subscripts denote the factor pairs. For all four crops, this estimated elasticity of substitution is low (approximately 0.09 for wheat, 0.10 for soybeans, 0.11 for corn, and 0.06 for cotton) but not unreasonable for crop specific data since some of the substitution possibilities in aggregate studies must be the result of crop switching. These figures may be compared with Binswanger's estimate of the elasticity of substitution between land and labor for aggregate United States data of 0.204, or Lopez's estimate for Canadian agriculture of 0.113.

The biological TC estimates reported in the second column tend to conform to normal preconceptions of fertilizer responsiveness, with corn showing the largest coefficient while the estimates for cotton and soybeans are considerably lower. The third column shows that the mechanical TC estimates appear to be a function of economic forces.[6] Wheat and soybeans were much less labor-intensive than corn and cotton at the beginning of the period and show far lower rates of labor-saving TC.

The coefficients for the inputs[7], reported in columns (4) to (7) also appear to conform

[4]The effects of interdependent lag structures, varying lag lengths, and comparing main regions with regions of lesser importance, or applying regional weights in the regressions, were not very enlightening. The more interesting results on returns to scale and inter-temporal changes in technical progress are reported.

[5]The constant returns to scale constraint is explained and discussed in the next section, where it is dispensed with in order that returns to scale may be considered. Experimentation with the structure of the model and the data available are considered at the end of this section.

[6]Hypothesis testing requires calculation the log of the likelihood function (Dhrymes, p. 279) for constrained and unconstrained versions of the model in order that this ratio may be used for the Chi square test described by Theil (1971, pp. 396-7). Constrained models in which $\rho = 0$ (which reduces the model to the Cobb Douglas) and $\delta = \gamma$ (neutral technical change) were clearly rejected for all crops. In fact, in all cases where tests were performed to determine whether two parameters were significantly different, (both within and between crops) the model fitted tightly enough for the constraint to be rejected.

[7]The coefficients reported play a major role in determining the values of the output elasticities, which are not independent of the variables. For example, the output elasticity for land is:

$$\frac{\partial Q}{\partial A} \cdot \frac{A}{Q} = \alpha\theta(Q/A^{\alpha}F^{\Phi})^{\rho}.$$

Thus, comments on the reported coefficients cannot include comparisons between crops or between the two input groups. This required estimates of the distribution parameters and evaluation of the output elasticities for fixed values of the variables, a process which added little information of interest.

TABLE 1. ESTIMATES OF TECHNICAL CHANGE PARAMETERS FOR SELECTED FIELD CROPS, UNITED STATES, 1939-78[a]

	Technical change parameters							
Crop	(1) Substitution, ρ	(2) Biol. gical, δ	(3) Mechanical, ν	(4) Land, α	(5) Ferti-lizer $1\text{-}\alpha$	(6) Labor, λ	(7) Machinery $1\text{-}\lambda$	(8) Elasticity of adjustment
Wheat	11.26	0.015	0.024	0.61	0.39	0.46	0.54	0.45
Soybean	10.08	0.011	0.025	0.72	0.28	0.53	0.47	0.46
Corn	8.95	0.017	0.063	0.69	0.31	0.61	0.39	0.22
Cotton	15.90	0.005	0.047	0.72	0.28	0.57	0.43	0.31

[a] Three stage least squares estimates. The t statistic showed all estimates to be significant at the 99% confidence level except for biological change in cotton, which was significant at the 95% level. For the sixteen fitted equations the adjusted R-squared values averaged 0.90.

fairly well to prior expectations. In particular, fertilizer $(1-\alpha)$ is more important relative to land in the case of wheat and corn than for soybeans (which are relatively unresponsive to fertilizer) and cotton. Labor (λ) has lower coefficients relative to machinery for the less labor-intensive crops (wheat and soybeans) and conversely machinery appears to be most important in the case of wheat, followed by soybeans.

The final column reports the average adjustment elasticity for each crop (the average of a, b, c, and d in equations (9)-(12)), and shows that adjustment to long-run equilibrium appears to be faster for wheat and soybeans than for corn and cotton. Though the relative adjustment speeds of the four inputs are of interest, the 1 year lag structure imposed by the model tended to produce very similar figures for all four inputs. Hence, only the average of the four figures is reported in Table 1.

Several experiments were conducted to determine the sensitivity of the parameter estimates to changes in the structure of the model and the input series. Firstly, pesticide was included in the production function for all four crops, but the coefficient was not significantly different from zero except in the case of soybeans. Including pesticide in the land and fertilizer input group for soybeans resulted in a coefficient of 0.054; whereas, the value was not significantly different from zero if pesticide was included in the labor and machinery input group. This would suggest that the effect of pesticide in soybean production is largely yield-increasing and that pesticide is functionally separable from labor and machinery. This result agrees with Schroder et al. (1981) who have shown that pesticide use significantly increased yields in soybeans and corn.

Secondly, since the USDA machinery price series has been criticized by Griliches and others (such as Fettig) for failing to take account of quality changes, an alternative machinery input series was constructed. The machinery value series was deflated by the Bureau of Labor Statistics (BLS) farm machinery price index rather than the USDA index (Griliches (1960) argued that the specification of the BLS index is superior). Though the BLS-based series increased considerably faster, the effect on the parameter estimates was negligible. This fortunate result is a little surprising since the technical change parameters may be expected to be sensitive to the treatment of quality improvements.

FURTHER ISSUES

Binswanger et al. (p. 91-163) has introduced an induced innovation model that is more general than that of Hayami and Ruttan. They argue that,

> *It is neither factor prices alone, as in the Ahmad version of induced innovation, nor factor shares alone as in the Kennedy-Weizsacker-Samuelson version of induced innovation, that influence optimal research mix and hence rates and biases ... Considering factor prices alone neglects the importance of factor quantity in factor costs* (Binswanger et al., p. 139-40). Thus, they argue that, *if the initial production function is labor intensive, that is, if it requires large amounts of labor relative to capital, expected discounted wage costs will be higher than if the initial production function is capital intensive. Hence, for given factor cost ratios and innovation possibilities, labor-saving research is more attractive if one starts from a labor-intensive point than if capital intensity is already high* (p. 103).

TABLE 2. MEASURES OF THE LABOR-SAVING BIAS FOR SELECTED FIELD CROPS, UNITED STATES, 1939-78

Measures	Selected field crop				
				Cotton	
	Wheat	Soybeans	Corn	1939-78	1955-78
$\gamma-\delta$	0.009	0.014	0.046	0.042	0.054
$(\gamma-\delta)/\gamma$	0.375	0.560	0.730	0.890	1.000

This proposition can be tested for crops with different land/labor ratios. If the hypothesis is correct, the more labor-intensive a crop is, the more labor-saving crop specific technical change should be, *ceteris paribus*. This hypothesis can be tested using the results reported here.[8] At the beginning of the period, wheat was the least labor-intensive crop, followed by soybeans, corn, and cotton. The Binswanger et al. (Ch. 4) model of induced innovation clearly suggests that inducement will occur even at constant factor prices (unlike Hayami and Ruttan, pp. 125-8).

In Table 2 , two possible measures of the labor-saving bias at constant factor prices are shown, testing the implications of Binswanger's formulation of the inducement hypothesis. Estimates of the most obvious measure of the bias, $\gamma-\delta$ are reported in the first row which shows wheat, the least labor-intensive crop, to have the lowest labor-saving bias, followed by soybeans. Corn and cotton which are far more labor-intensive show a considerably greater degree of labor-saving bias, as predicted by the hypothesis. However, the bias for corn is slightly larger than for cotton, contrary to the predicted result. This finding arises from the fact that the massive exodus of share-croppers from the Delta and the old South did not occur until the mechanization of cotton harvesting in the 1950s (Day). For the period 1955-78, the technology coefficients for cotton are $\delta = 0.0$ and $\gamma = 0.054$, giving a labor-saving bias of 0.054 and reversing the ordering of corn and cotton to conform with the hypothesis.

David (pp. 42-4) has argued that the absolute measure of bias used above is inappropriate since it depends on the rate of technical change, and has suggested that the relative labor-saving bias $(\gamma-\delta)/\gamma$ is a better measure. The second row of Table 2 shows that if the relative bias is taken to be the correct measure, then there is no doubt that the more labor-intensive the crop, the greater the labor-saving bias in technical change, as predicted by the inducement hypothesis.

Binswanger's proposition may equally be applied to regions that began the period with relatively high and low labor-intensities, rather than to different crops. At the beginning of the period, the land/labor ratios for the Northern Plains, Corn Belt, and Lake States were far higher than those for the Southeast, the Delta, and Appalachia. Binswanger's statement of the inducement hypothesis predicts that the more labor-intensive regions may be expected to show a greater labor-saving bias in technical change.

This proposition was tested for the two groups of regions mentioned for the case of corn production (Corn has the advantage of being of some importance in both groups.). The labor-intensive group has higher estimated technical change parameters for both groups of factors, with a labor-saving bias, $(\gamma-\delta)$ equal to 0.075, while for the less labor-intensive regions the figure is 0.023. (These figures bracket the results for corn in all regions of 0.046 as indeed they should). Again, the implications of the induced innovation hypothesis are supported.

Though the technical change terms in Table 1 are constrained to remain the same over the entire 40-year period, the sample is of sufficient size to allow inter-temporal comparisons and thus investigate the evidence for changes in the rates of technical progress. This is of current interest since it has been suggested that the "productivity growth slowdown" that is apparent in United States industry may also have affected the agricultural sector. Paarlberg has argued that the losses due to factors such as erosion and urbanization can no longer be overcome by productivity gains. First, the efficiency generating backlog of technological improvements is all but used up and, secondly, the research community is not generating a suf-

[8]Though the biological TC terms were neutral with respect to land and fertilizer and the mechanical TC terms were neutral with respect to labor and machinery, the overall (between-group) rate of technical change is non-neutral, being land-saving if $\delta > \gamma$ and labor-saving if $\gamma > \delta$. Obviously, this (apparent) paradox is a function of the many-factor approach.

ficient flow of knowledge to maintain growth. It does appear to be true that,

federal contributions to the experiment stations have been virtually stagnant in real terms for 15 years,

(Paarlberg, p. 111). Lu et al. argue that research, development, and extension activities are insufficient to maintain historical growth rates. Similarly, the cost-benefit analysis of White and Havlicek shows large welfare losses to be the result of current low levels of government investment in research and extension.

For corn, the rates of both biological and mechanical TC appeared to be incredibly consistent over the entire period. In cotton, the only discernible change was the increased rate of mechanical TC from the mid-1950s onwards, already discussed. Soybeans appeared to show more rapid rates of TC before 1950, with no changes in the rates after that date. However, in the case of wheat, Table 3, suggests that the sample can be split into four distinct decades.

TABLE 3. TECHNICAL CHANGE IN WHEAT PRODUCTION BY TIME PERIOD, UNITED STATES, 1939-78

	Time period			
Item	1939-48	1949-59	1960-70	1971-78
Biological TC (δ)	0.012	0.031	0.022	0.012
Mechanical TC (γ)	0.006	0.047	0.025	0.007

For the 1940s, both biological and mechanical TC parameters are exceptionally low at 1.2 percent and 0.6 percent per annum, respectively. For the 1950s, there is a tremendous increase to 3.1 percent and 4.7 percent. In the 1960s, the rates fall to 2.2 percent and 2.5 percent, while the decade of the 1970s is as little as the first period. The suggestion that the "technological backlog" has been mostly used up seems to be true in the case of wheat production. For the period from 1971 to 1978, biological TC only accounts for 1.2 percent of output per annum, while mechanical TC is only 0.7 percent. The downturn does appear to begin in 1971 rather than 1973, which is the year in which Heid (p. iii) suggests that United States wheat yields leveled off, and it appears to be labor-saving mechanical TC rather than yield-increasing biological change that has dropped most significantly. This result would suggest that the decline cannot be entirely attributed to the expansion of the wheat acreage on marginal land in response to the higher prices of the 1970s.

The previous analysis concentrated on technical change and avoided the issue of returns to scale by imposing homogeneity of degree one. This restriction is now removed. However, the meaning of "returns to scale" in aggregate studies of this nature is less than obvious. Walters argues that in cross section studies using aggregated data, no inferences can be drawn concerning returns to scale. In this study, the unit of observation is the farm production region, not the farm. Thus, in the case of wheat, if regions like the Northern Plains that account for a large proportion of output are more efficient than regions like the Southeast that account for a small proportion of output, there will appear to be increasing returns. However, if the Northern Plains area was separated into smaller areas such as counties, there would be no real change in efficiency but the small regions would then appear to be more efficient than the large and the "pseudo increasing returns" would become "pseudo decreasing returns." The time series aspect of the data complicates the issue but does not fundamentally change it. Hence, linear homogeneity was improved in the previous section. The alternative is to follow Griliches (1964) in dividing all the variables for each region by the number of farms in that region, so that the transformed data may be interpreted as representing the average sized farm.

Since it can be shown (Thirtle, 1982) that the output elasticities sum to:

$$\frac{(\alpha+\varphi)\theta(A^{\alpha}F^{\Phi}e^{\delta_t})^{-\rho} + (\lambda+\mu)\eta(L^{\lambda}M^{\mu}e^{\gamma_t})^{-\rho}}{\theta(A^{\alpha}F^{\Phi}e^{\delta_t})^{-\rho} + \eta(L^{\lambda}M^{\mu}e^{\gamma_t})^{-\rho}},$$

if the estimated coefficients are such that $\alpha + \varphi = 1$ and $\lambda + \mu = 1$, then constant returns to scale hold. This result is not surprising since requiring each pair to add to unity is imposing the normal Cobb Douglas requirement. Removing this constraint and transforming the variables produces the parameter estimates shown in Table 4.

TABLE 4. ESTIMATES OF RETURNS TO SCALE FOR SELECTED FIELD CROPS, UNITED STATES, 1939-78

Parameter estimates	Selected field crop			
	Wheat	Corn	Soybeans	Cotton
$\hat{\alpha} + \hat{\varphi}$	1.05	1.01	0.98	1.08
$\hat{\lambda} + \hat{\mu}$	1.17	1.06	0.98	1.02

These estimates suggest increasing returns may be important in wheat but considerably less so in corn and cotton, while soybeans show some evidence of decreasing returns to scale. These figures are considerably lower than the values reported by Griliches (1964) at the region level of between 1.352 and 1.362 and at the state level of between 1.192 and 1.282 (Griliches, 1963). It would appear that the mean differencing technique has effectively removed regional efficiency differences, preventing over-estimates of returns to scale of the type discussed by Kislev and Mundlak.

CONCLUSION

The results reported here suggest that technical change in United States field crops shows a clear labor-saving bias (relative to land). There are considerable differences between crops that are usually lost in the aggregation process. Particularly, the more labor-intensive the crop, the greater the labor-saving bias in technical change, as predicted by the induced innovation hypothesis. The effect of 40 years of differential biases in technical change has been to all but remove the initial disparities in land/labor ratios. Since some proportion of factor substitution in United States agriculture must be attributable to crop switching, the importance of factor substitution must have diminished over the period. Furthermore, the pronounced labor-saving bias over the period considered has changed United States agriculture from a labor-intensive activity to one of the most capital-intensive industries in the United States. Combined with the recent rapid increase in the relative price of land, this could lead to major changes in the factor-saving biases of agricultural research and hence of factor proportions in the future. Indeed, the induced innovation hypothesis would predict such a change.

Finally, though the rate of technical change in wheat production appears to have declined considerably in the 1970s, there was no evidence of a general "productivity slowdown." Corn, soybeans, and cotton showed no decline in rates of technical change. This result does suggest that up to 1978, the effects of soil erosion and urbanization were still more than compensated for by technical change. Unfortunately, the estimates for wheat show that it is labor-saving mechanical technical change that has declined most severely. If the limits of mechanization have been reached in wheat production, the other field crops must be expected to follow. The trend in wheat production may well prove to be a leading indicator of the path the aggregate will follow.

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