Volume Title: New Developments in Productivity Analysis

Volume Author/Editor: Charles R. Hulten, Edwin R. Dean and Michael J. Harper, editors

Volume Publisher: University of Chicago Press

Volume ISBN: 0-226-36062-8

Volume URL: http://www.nber.org/books/hult01-1

Publication Date: January 2001

Chapter Title: Total Resource Productivity. Accounting for Changing Environmental Quality

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Chapter URL: http://www.nber.org/chapters/c10135

Chapter pages in book: (p. 587 - 608)

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Total Resource Productivity Accounting for Changing Environmental Quality

Frank M. Gollop and Gregory P. Swinand

The formal transfer of intellectual dominance from labor productivity to total factor productivity (TFP) celebrated its fortieth anniversary last year. Solow (1957) made clear that measures of efficient resource use should not and need not exclude nonlabor inputs. Many economists took up the challenge and while debate raged over various measurement issues ranging from the treatment of economic depreciation[1] to changing input quality,[2] consensus quickly formed around the superiority of the basic TFP framework. All marketable inputs were to have equal stature in a formal model of productivity measurement.

The prima facie case for further broadening the concept of productivity to include nonmarket resources is equally self-evident. Proper measures of productivity growth are barometers of how well society is allocating its scarce resources. In this context, there is little difference between labor, capital, and material inputs, on the one hand, and air and water resources, on the other. Each is scarce. Consumption of any one entails true opportunity costs. Market failures may generate measurement difficulties, especially with respect to prices, but are not sufficient to justify excluding nonmarket resources from a model of productivity growth. After all, at its most fundamental level, productivity growth is a real, not nominal, concept. The case for expanding TFP to total resource productivity (TRP) is compelling.

What is less self-evident is how to measure TRP. Certainly there are a

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1. See Denison (1969, 1972) and Jorgenson and Griliches (1972a, 1972b).
2. See Jorgenson and Griliches (1967), Denison (1979), and Kendrick (1961, 1973).

number of alternatives presented in the literature. Repetto and colleagues (1996) offer an intuition-based generalization of the traditional growth accounting framework. Ball, Färe, Grosskopf, and Nehring (chap. 13, this volume) propose a nonparametric formulation based on activity analysis. There is the temptation to engage in debates about approach (growth accounting, econometrics, or activity analysis) and issues of mathematical formalism, but proper TRP measurement begins from a much more fundamental issue. TRP measurement requires choosing between competing production and welfare-based paradigms, a distinction that is moot for traditional TFP accounting, which considers only outputs and inputs that have well-oiled, perfectly competitive market transactions. Measures of TRP in contrast, cannot ignore jointly produced externalities and market failures. At a minimum, equilibrium conditions (and therefore productivity weights) based on producers' marginal abatement costs are certain to be different from equilibrium conditions based on shadow prices consistent with a model of consumer welfare.

The objective of this paper is to suggest a proper framework for TRP measurement. The paper begins from the premise that TRP measurement is fundamentally a production issue. This follows from the very definition of productivity growth—the changing efficiency with which society transforms its scarce resources into outputs. Traditional productivity measures derived from models of market-based producer behavior have no difficulty satisfying this criterion; neither do properly conceived welfare-based models. The welfare-based model introduced in this paper indeed derives formally from a model of welfare maximization. In this respect, it does depart from the producer perspective common to mainstream productivity work. However, it does not define TRP growth as the net growth in welfare, but as the net growth in social output within the welfare function. It effectively adopts a household-based production approach and thereby is wholly consistent with the evolution of productivity measurement over the past forty years. Viewed in this light, neither the producer nor the welfare-based models introduced later can be judged intellectually superior to the other. They simply are different in two critical respects. First, although the undesirable by-product enters the welfare function directly, how it enters a production-based model is determined by the form of environmental regulation conditioning producer behavior. In short, environmental output may enter differently into producer- and welfare-based models. Second, producers' valuation of the by-product in terms of its marginal abatement cost is likely to differ from society's shadow valuation. In short, the two models originate from different characterizations of economic objectives and models of producer behavior. The producer- and welfare-based models are developed in sections 14.1 and 14.2, respectively. Using data for the U.S. farm sector, TRP measures corresponding to the two models are compared in section 14.3 and contrasted with the conventional TFP measure.

The specific properties of the TRP models are derived and described in detail in the following sections, but before engaging in mathematical formalism, two preliminary observations are in order. First, the TRP models introduced below are derived wholly within the familiar growth accounting paradigm. Models of producer and consumer behavior, equilibrium conditions, and familiar lemmas underlie the models. The ease with which the traditional growth accounting framework can be modified to embrace environmental issues in both traditional producer and now welfare contexts is a testimonial to the resilience of growth accounting. The relative merits of alternative approaches can and should be openly debated, but a subliminal objective of this paper is to demonstrate that our collective excursion into environmental issues need not abandon the growth accounting framework. Second, the reader may have noticed that when this introduction motivates the broadening of standard production theory to accommodate environmental issues, the discussion sometimes references environmental variables in the context of inputs (e.g., air and water resources) and sometimes in the context of production by-products (dirty air and water). This should not be interpreted as ambivalence, but as true indifference. There is a one-to-one mapping between environmental resource consumption and the production of environmental by-products. In terms of production accounts, modeling the consumption of environmental resources as inputs is identical in concept and measure to modeling the environmental consequence as an output. This particular paper characterizes the environmental variable as an output, but the models and their conclusions would be unaffected if it were treated as an input. Neither approach can finesse the pricing problem. The environmental variable, whether modeled as an input or as an output, requires a shadow price, identical except for sign. In the context of environmental variables, environmental outputs are just the negative of environmental inputs. Not surprisingly, symmetry applies.

14.1 A Producer-Based Model

Consider an economy endowed with resources $\underline{X}$ and technology T. The economy produces a conventional output Y and, as a joint-production by-product, an undesirable output S. Assume that the production of Y is the only source of S.[3] The byproduct S enters the economy's production accounts because of regulatory constraints on S. Producers are held accountable, and therefore S enters the model of producer behavior.

Developing an index of the production sector's aggregate output begins

3. Relaxing this assumption would lead to different measures of S entering the economy's production and welfare functions. Only those units of S originating in formal production processes would enter production functions; all S, regardless of source, would enter the welfare function. This complication is unnecessary given the objective of this paper.

by selecting any arbitrary set of nonnegative quantities of outputs Y and S.[4] Given this product set, the economy's aggregate output can be defined as a proportion of quantities of outputs Y and S or, equivalently, as a proportion of conventional output Y holding fixed its environmental quality S/Y. The maximum value of aggregate output (Φ) then can be expressed as a function of Y, its environmental quality S/Y, resources $\underline{X}$, and a time-based technology index T:

$$\Phi = H(Y, S/Y, \underline{X}, T). \tag{1}$$

Though the definition of Φ can accommodate the characterization of S in equation (1) in either ratio (S/Y) or level (S) form, the choice of the ratio form in equation (1) is not the result of mathematical indifference. How S enters the production account is determined by the particular form of regulation. Typically, environmental regulations take the form of rates rather than levels. For example, in the farm sector (the industry selected to illustrate TRP measurement in section 14.3), environmental restrictions for fertilizers and pesticides are posed in terms of application rates per acre planted, not in terms of total tons of pesticides and fertilizers used in U.S. agriculture. Emission standards for automakers are another example. In other industry/pollutant contexts, it may be more appropriate to specify that the byproduct should enter equation (1) as a level, but for present purposes the environmental constraint and therefore the measure of environmental output enters the production account in equation (1) and the resulting model of producer behavior as S/Y. The firm uses resources $\underline{X}$ and technology T to produce two outputs: the marketable output Y and the regulation-mandated output S/Y.

The marginal rates of transformation among the arguments in equation (1) are of note. The function H is increasing in S/Y, $\underline{X}$, and T and decreasing in constant quality output Y. Ceteris paribus, an increase in S/Y (holding Y fixed) frees resources to produce additional aggregate output Φ; an increase in Y consumes resources and therefore reduces aggregate output. There is a positive rate of transformation between Y and S/Y.

The function H exhibits the usual homogeneity properties. H is homogeneous of degree minus one in Y and S because, holding S/Y, $\underline{X}$, and T constant, any proportional increase in Y and S definitionally generates an equal proportional decrease in Φ. In addition, H is assumed to be homogeneous of degree one in $\underline{X}$. As a result, H is homogeneous of degree zero in Y, S, and $\underline{X}$ and exhibits constant returns to scale.

The graphical presentation in figure 14.1 is instructive. Consider an economy producing a single conventional output Y and an undesirable

4. At this stage of the analysis, there is no requirement that the selected output levels Y and S be feasible given X and T. The only requirement is that Y and S be nonnegative.

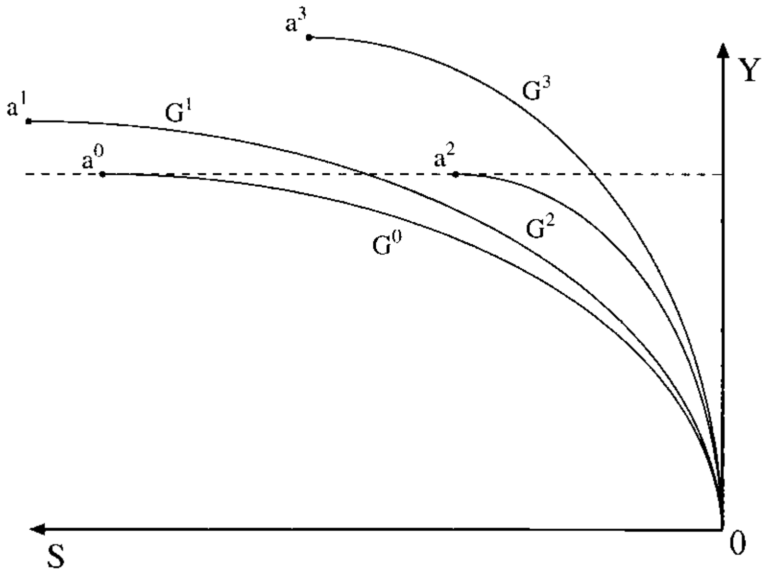

Fig. 14.1 Properties of production possibilities frontiers in conventional (Y) and undesirable (S) outputs

output S. The natural reference point or origin for this analysis is $Y = S = 0$. Because Y is a "good" and S is a "bad," the second quadrant provides the appropriate context. Given $\underline{X}$ and T, the economy can operate efficiently anywhere along its production possibility frontier G^0 defined between the origin and point a^0. Starting G^0 at the origin posits that (a) there is no costless (input free) way to produce Y, and (b) the production of Y is the only relevant source of the by-product S.[5] Production beyond (to the left of) a^0 is economically irrelevant. At point a^0, the economy dedicates all $\underline{X}$ to the production of Y and none to the abatement of S. It follows that production of conventional output Y and by-product S reach their maximums at a^0.

The frontier G^0 has the usual negative slope and smooth curvature indicating that the marginal cost of producing Y and the marginal abatement cost of reducing S are both increasing in their respective arguments. Note, as the economy approaches a^0 along G^0, the marginal abatement cost of S approaches zero.

Increased resource endowments and technical change lead to shifts in the frontier. An increase in $\underline{X}$ leads to frontiers of the form G^1, which, like

5. Either or both of these conditions could be relaxed without affecting the analysis that follows. Both are maintained for convenience.

G^0, begins at the origin but reaches its maximum at a point a^1 northwest of a^0, implying that, without a change in technology, added production of Y with zero abatement necessarily implies additional S. In the event of technical change, the frontier shifts up, but the frontier's zero abatement boundary depends on the nature of technical change. If technical improvements are embedded solely in the production of Y, the point of maximum possible Y and zero abatement will occur to the left of a^0, as is the case for frontier G^1. If, however, the process of S abatement is the sole source of technical change, then frontier G^0 might shift to take the form represented by G^2, where production of maximum Y (unchanged from G^0) with zero abatement leads to a lower level of S. Technical improvements reflecting efficiency gains in both the production of Y and the abatement of S would lead to frontiers of the form G^3.

Returning to the more general representation H, the task of the producing sector of the economy is to maximize production given the supplies of primary factors of production $\underline{X}$, the sectoral production functions summarized in the technology variable T, market equilibrium conditions for inputs $\underline{X}$ and conventional outputs $\underline{Y}$, and existing societal restrictions (if any) on S/Y. Full compliance is assumed.

Deriving the model of productivity growth for the economy represented by the aggregate production function H begins by setting aggregate output Φ equal to unity. It is important to emphasize that fixing Φ at unity does not imply that output does not or cannot change over time. Given the negative one-to-one relationship between Φ and the scale of conventional output $\underline{Y}$, output growth can be represented either by an increase in Φ or, equivalently, by an identically proportional increase in Y. Fixing Φ at unity does nothing more than force growth to be reflected in the Y variable.

The representation of H now takes the form of the familiar production possibilities frontier:

$$(2) \qquad 1 = H(Y, S/Y, \underline{X}, T)$$

Taking the logarithmic differential of equation (2) with respect to time and solving for $\partial \ln H/\partial T$ yields the following formulation for the production sector's rate of productivity growth (TRP^{P}):

$$(3) \qquad \text{TRP}^{\text{P}} \equiv \frac{\partial \ln H}{\partial T} = -\frac{\partial \ln H}{\partial \ln Y}\frac{d \ln Y}{dT} - \frac{\partial \ln H}{\partial \ln(S/Y)}\left[\frac{d \ln S}{dT} - \frac{d \ln Y}{dT}\right] - \sum_i \frac{\partial \ln H}{\partial \ln X_i}\frac{d \ln X_i}{dT}.$$

Necessary conditions for producer equilibrium in a competitive economy transform the logarithmic partials in equation (3) into well-defined variables:

$$(4)\qquad \frac{\partial \ln H}{\partial \ln Y} = -\frac{qY}{P_\Phi \Phi} = -1$$

$$\frac{\partial \ln H}{\partial \ln (S/Y)} = \frac{\rho S}{P_\Phi \Phi} = \frac{\rho S}{qY}$$

$$\frac{\partial \ln H}{\partial \ln X_i} = \frac{w_i X_i}{P_\Phi \Phi} = \frac{w_i X_i}{qY} \qquad (i = 1, 2, \ldots, n),$$

where P_Φ is the unit price of aggregate output, q is the unit price of conventional output Y, the w_i represent input prices, and ρ equals the marginal abatement cost of S. It is important to note that the partial derivative in the first line of equation (4) is taken with respect to marketable output Y holding constant its environmental quality content S/Y. This, together with the assumption of a competitive market for Y, permits the necessary condition to be expressed in terms of q, the *observed* market price of Y—a desirable property of a model destined for empirical application. Note also that the value of aggregate output $P_\Phi \Phi$ equals the value of marketable output qY. This follows from the assumption of competitive markets and the definitions of H and Φ. The producers' abatement costs are reflected in both q and P_Φ.

The definition of H and the competitive nature of markets for $\underline{X}$ and Y also guarantee

$$(5)\qquad \sum_i \frac{w_i X_i}{qY} = 1.$$

This follows from the economic characterization of production and competitive markets for Y and $\underline{X}$. First, abatement requires resources $\underline{X}$ so that $\Sigma w_i X_i$ captures the total cost of producing Y as well as abating pollution to the given level S/Y. Second, the competitive market price q reflects the marginal cost of both producing Y and engaging in abatement to the level S/Y. It follows that $qY = \Sigma w_i X_i$ as required by equation (5).

Making the necessary substitutions from equation (4) into equation (3) yields the formula for measuring TRP^{P} conditioned on a model of producer equilibrium

$$(6)\qquad \text{TRP}^{\text{P}} = \frac{d \ln Y}{dT} + \frac{\rho S}{qY}\left[\frac{d \ln Y}{dT} - \frac{d \ln S}{dT}\right] - \sum_i \frac{w_i X_i}{qY} \cdot \frac{d \ln X_i}{dT}.$$

TRP growth equals the growth in marketable output plus the weighted growth in the product's environmental quality (positive [negative] if $d \ln Y/dT > [<]\, d \ln S/dT$) less cost-share weighted input growth.

The specification of TRP^{P} is consistent with the legacy of TFP modeling. The underlying notion of productivity growth is defined wholly from the producers' perspectives. Necessary conditions for producer equilibrium are used to weight all outputs (Y and S/Y) and inputs. As technical change occurs and Y and S/Y grow at different rates, substitution possibilities are evaluated along production possibilities frontiers.

The measure TRP^{P} has some very nice properties. If, as output grows, either the pollution content per unit of output does not change ($d\ln Y/dT = d\ln S/dT$) or marginal abatement cost is zero ($\rho = 0$), then TRP^{P} in equation (6) collapses to the traditional TFP form. In the former case, the producer receives credit only for the growth in Y—exactly as in the TFP framework. In the latter instance, although S may be an undesirable by-product of production, society has chosen to impose no binding restriction ($\rho = 0$) on producer behavior. Producers behave rationally and allocate no resources to abatement. (When $\rho = 0$, TRP growth is modeled from peak to peak (at points "a") in figure 14.1.) Productivity growth, viewed from the perspective of the production sector, is properly measured as TFP. However, should society impose a binding regulatory constraint on producers, then, because reducing S/Y is costly in terms of $\underline{X}$ or foregone marketable Y, $\rho > 0$ and the producing sector is induced to consider the S content of its output Y. Consequently, when $\rho > 0$, proper productivity measurement cannot ignore changes in S/Y. Given $\rho > 0$, TRP^{P} must "grade" producers for changes in environmental quality per unit of output. Ceteris paribus, TRP^{P} growth > (<) TFP growth when the production sector improves (diminishes) the environmental quality of its product. Stated formally, if $\rho > 0$ and $d\ln Y/dT \neq d\ln S/dT$, productivity growth should be measured as a shift in production frontiers defined on both Y and S/Y. Ignoring the nonmarket output term S/Y in equation (6) would lead to a biased measure of producer-based productivity growth.

14.2 A Welfare-Based Model

The notion of productivity growth has stand-alone integrity. It derives from an analysis of the sources of output growth. It equals the weighted growth in output less the weighted growth in inputs. Developing a welfare-based framework for evaluating productivity growth does not challenge this orientation. There is no attempt to replace output growth with welfare growth.

The definition of productivity growth is not at issue. What is at issue is the definition of output and the formulation of the weights in the productivity formula. First, regulatory mandates may be such that the by-product S enters the definition of aggregate output for the production sector differently than it does the societal definition of aggregate output. Second, conventional output, inputs, and the undesirable by-product are weighted differently in the two models. A production-based model relies on relative valuations as defined by marginal rates of transformation along the production possibilities frontier, whereas a welfare-based paradigm is based on marginal rates of substitution defined by the welfare function. Given market failure, marginal rates of transformation and substitution are likely to differ. What is important to emphasize is that the notion of productivity growth as a production concept is not in dispute. The task is to specify aggregate output properly and determine the proper formulation of the value weights for inputs and outputs.

Consider a welfare function U for a representative single-consumer economy

$$U[Y, S, \underline{Z}], \tag{7}$$

where U is a function of marketable output Y, the production by-product S, and a vector of other variables $\underline{Z}$ that may affect welfare. It is assumed that $\partial U/\partial Y > 0$ and $\partial U/\partial S < 0$. Note that S enters equation (7) as a level, not in the form of a ratio. Although producers in the economy's production sector may be conditioned by regulation to denominate environmental output on a per marketable unit basis (S/Y), it is assumed that consumer welfare is affected by overall environmental quality, the aggregate amount of S.

It is further assumed that Y and S are separable from $\underline{Z}$ and that their resulting aggregate defines societal output Ω:

$$U[\Omega(Y, S), \underline{Z}]. \tag{8}$$

where $\partial U/\partial\Omega > 0$; $\partial\Omega/\partial Y > 0$, and $\partial\Omega/\partial S < 0$. As a result, the analysis can proceed by evaluating productivity growth through the separable subfunction U^0:

$$U^o[\Omega(Y, S)]. \tag{9}$$

Paralleling the above derivation for aggregate output in the production sector, developing a measure of aggregate societal output in terms of its underlying arguments begins by selecting any arbitrary set of nonnegative quantities of Y and S. Given this product set, Ω is defined as a proportion of quantities of marketable output Y and the byproduct S. The maximum value of societal output Ω can then be expressed as a function of Y, overall environmental quality S, resources $\underline{X}$, and the production sector's technology T:

$$\Omega(Y, S) = G(Y, S, \underline{X}, T), \tag{10}$$

where $\partial G/\partial Y < 0$, $\partial G/\partial S > 0$, $\partial G/\partial X_i > 0$, and $\partial G/\partial T > 0$. It follows that

$$U^0[\Omega(Y, S)] = U^0[G(Y, S, \underline{X}, T)]. \tag{11}$$

The representative consumer maximizes U^0 subject to the usual budget constraint

$$M \equiv qY - \sum w_i X_i , \tag{12}$$

where M is money income. Solving this problem leads to the usual set of necessary conditions for consumer equilibrium:

$$\begin{aligned} \frac{\partial U^0}{\partial G} \cdot \frac{\partial G}{\partial Y} + \lambda q &= 0. \\ \frac{\partial U^0}{\partial G} \cdot \frac{\partial G}{\partial S} - \lambda \eta &= 0 \\ \frac{\partial U^0}{\partial G} \cdot \frac{\partial G}{\partial X_i} - \lambda w_i &= 0 \qquad (i = 1, 2, \ldots, n), \end{aligned} \tag{13}$$

where λ is the Lagrange multiplier representing the marginal utility of money income and η is the absolute value of the shadow price of S, the marginal disutility of an additional unit of S.

The objective is to define the welfare-based rate of productivity growth through the societal production function G as valued by society (i.e., through the eyes of a representative consumer). To this end, productivity growth is defined as the rate of growth in aggregate social output (Ω) net of input growth, where all outputs (Y, S) and inputs ($\underline{X}$) are valued by relative prices reflecting the consumer's marginal rates of substitution. This definition of productivity growth is operationalized by setting Ω equal to unity, thereby transforming $G(\cdot)$ in (10) into a social production possibilities frontier and taking the total differential through $U^0[G(Y, S, \underline{X}, T)]$:

$$0 = \frac{\partial U^0}{\partial G} \cdot \frac{dY}{dT} + \frac{\partial U^0}{\partial G} \cdot \frac{\partial G}{\partial S} \cdot \frac{dS}{dT} + \sum_i \frac{\partial U^0}{\partial G} \cdot \frac{dX_i}{dT} + \frac{\partial U^0}{\partial G} \cdot \frac{\partial G}{\partial T}. \tag{14}$$

Substituting equilibrium conditions from equation (13), multiplying all terms by well-chosen "ones," and dividing all terms by the marginal utility of income (λ or its equivalent $\partial U^0/\partial G \cdot \partial G/\partial M$) yields

$$0 = qY \frac{d \ln Y}{dT} - \eta S \frac{d \ln S}{dT} - \sum w_i X_i \frac{d \ln X_i}{dT} + \frac{\frac{G \partial U^0}{\partial G} \cdot \frac{\partial \ln G}{\partial T}}{\frac{\partial U^0}{\partial G} \cdot \frac{\partial G}{\partial M}}. \tag{15}$$

Recognizing that $\partial G/\partial M = 1/P_G$, welfare-based productivity growth ($\mathrm{TRP^W}$) can be derived by dividing all terms in equation (15) by $P_G G$ and solving for the last term in equation (15):

$$\mathrm{TRP^W} \equiv \frac{\partial \ln G}{\partial T} = \frac{qY}{P_G G} \frac{d \ln Y}{dT} - \frac{\eta S}{P_G G} \frac{d \ln S}{dT} - \frac{\sum w_i X_i}{P_G G} \frac{d \ln X}{dT}. \tag{16}$$

Finally, since $qY = M$ and $P_G G = P_\Omega \Omega = (M - \eta S)$,

$$(17) \qquad \mathrm{TRP}^{\mathrm{W}} = \left(\frac{M}{M - \eta S}\right)\frac{d\ln Y}{dT} - \left(\frac{\eta S}{M - \eta S}\right)\frac{d\ln S}{dT} - \sum\left(\frac{w_i X_i}{M - \eta S}\right)\frac{d\ln X_i}{dT}$$

so that

$$(18) \qquad \mathrm{TRP}^{\mathrm{W}} = \left(\frac{M}{M - \eta S}\right)\left[\frac{d\ln Y}{dT} - \frac{\sum w_i X_i}{M}\frac{d\ln X_i}{dT}\right] - \left(\frac{\eta S}{M - \eta S}\right)\frac{d\ln S}{dT}$$

and

$$(19) \qquad \mathrm{TRP}^{\mathrm{W}} = \left(\frac{M}{M - \eta S}\right)\mathrm{TFP} - \left(\frac{\eta S}{M - \eta S}\right)\frac{d\ln S}{dT}.$$

The welfare-based measure of TRP equals a share-weighted average of the net contribution (net of input growth) of the growth in marketable output from the production sector (i.e., TFP growth) and the growth in the undesirable by-product S. The share weights reflect relative consumer valuations of Y and S.

$\mathrm{TRP}^{\mathrm{W}}$ has a number of attractive properties. First, equation (19) makes clear that changes in S have stand-alone importance in the $\mathrm{TRP}^{\mathrm{W}}$ formula. The traditional contribution of TFP to $\mathrm{TRP}^{\mathrm{W}}$ is augmented (diminished) through reductions in (additions to) S. Assuming $\eta > 0$, any decrease (increase) in S makes a positive (negative) contribution to $\mathrm{TRP}^{\mathrm{W}}$. Second, even if there is no change in S ($d \ln S/dT = 0$), $\mathrm{TRP}^{\mathrm{W}}$ does not collapse to TFP growth. This result is guaranteed by the weight on TFP in equation (19), $[M/(M - \eta S)] > 1$. Consider just two examples. First, assume inputs have not changed but conventional output Y has increased while S does not change. Conventional TFP is positive but is a downward-biased measure of true productivity growth because the growth in Y has been achieved without any increase in S. Second, assume that both conventional output and S remain unchanged whereas input requirements have decreased. Once again, TFP is positive but provides a downward-biased measure of $\mathrm{TRP}^{\mathrm{W}}$ because the output level of Y has not been maintained at the expense of environmental quality. Third, if reductions in S are of no value to consumers (and, symmetrically, increases in S generate no marginal damage), $\mathrm{TRP}^{\mathrm{W}}$ collapses to traditional TFP growth.[6] In this in-

6. Equations (17) to (19) suggest that if input growth were zero and the growth rates of Y and S were identical, then the growth rates of $\mathrm{TRP}^{\mathrm{W}}$ and conventional TFP would be equal. One should not infer from this, however, that because equal changes in Y and S affect TFP

stance, consumers marginal valuation of S (η) is zero. In this respect, the formula for TRP^{W} in equation (19) when $\eta = 0$ behaves just as does the formula for TRP^{P} in equation (6) when $\rho = 0$.

The relationship between TRP^{W} and TRP^{P} can be demonstrated by adding and subtracting

$$(20)\qquad \pm\left(\frac{\rho S}{M - \eta S}\right)\left(\frac{d\ln Y}{dT}\frac{d\ln S}{dT}\right)$$

to equation (18), whereby

$$(21)\qquad \text{TRP}^{\text{W}} = \left(\frac{M}{M - \eta S}\right)\text{TRP}^{\text{P}} - \left(\frac{\rho S}{M - \eta S}\right)\frac{d\ln Y}{dT} + \frac{(\rho - \eta)S}{M - \eta S}\frac{d\ln S}{dT}.$$

The second term on the right-hand side of equation (21) adjusts for the difference in the definitions of the production sector's aggregate output $\Phi(Y, S/Y)$ and aggregate societal output $\Omega(Y, S)$. Ceteris paribus, proportional increases in Y and S reduce the measure of environmental quality in Ω but leaves Φ unaffected. The second term in equation (21) permits the necessary transformation between TRP^{W} and TRP^{P}.

The last term in equation (21) is of more interest. This term is nonzero if and only if the marginal abatement cost of $S(\rho)$ does not equal the dollar value of marginal disutility associated with $S(\eta)$. The magnitude of the term reflects the difference between marginal rates of transformation and substitution in H and G, respectively. If $\rho = \eta$, the last term vanishes and the difference between TRP^{W} and TRP^{P} reduces to their different characterizations of aggregate output. However, if $\rho \neq \eta$, an additional issue of resource allocation creates a spread between TRP^{W} and TRP^{P}. For example, if $\eta > \rho$, then the marginal benefit of further reductions in S exceeds their marginal abatement cost so that those reductions contribute to TRP^{W} above their expected contributions through TRP^{P}. The key insight is a simple one. Just as differences in market prices and marginal costs impact the measurement of productivity growth in the face of imperfect product markets,[7] differences between shadow prices and marginal abatement costs have equal relevance in the context of market failure.

and TRP^{W} identically, TRP^{W} is not a negative function of S. The structure of equation (17) makes clear that, ceteris paribus, welfare is adversely affected by any increase in S. Nonetheless, if Y and S increase at identical rates, TFP growth is an unbiased measure of TRP^{W} growth. The explanation follows from standard productivity accounting. Placing 100 percent weight on the growth of a single output in a true multiple-output setting introduces no bias if all outputs happen to grow at the same rate. In the scenario set up in this note, if S happens to grow at the same rate as Y, TFP introduces no bias by ignoring S. However, if the growth rates of S and Y differ, TFP growth is a biased measure of TRP^{W} growth.

7. See Gollop (1987).

14.3 An Application to the U.S. Farm Sector

The objective of this paper is to suggest a proper framework for TRP measurement. To that end, it seems instructive to engage in an empirical exercise to compare and contrast traditional TFP with TRP^P and TRP^W measures. Given changing production practices in agriculture and preliminary data now available on the industry's environmental output, the U.S. farm sector becomes a logical candidate for an application of TRP accounting.

The modern production techniques that have enabled the U.S. farm sector to enjoy high rates of productivity growth necessarily require the use of pesticides, herbicides, and fungicides. The quality of surface water and groundwater sources are clearly affected by the application of these materials. Over time, application practices and chemical types and potency have been modified to mitigate harm to water quality through chemical runoff and leaching while preserving production levels of farm output. Properly designed measures of TRP^P and TRP^W should reflect this history.

Applying the TRP formulas described in sections 14.1 and 14.2 requires (a) price and quantity data on both conventional animal and crop outputs and labor, capital, and material inputs; (b) quantity data on the industry's environmental impact (S); and (c) estimates of both the sector's marginal abatement cost (ρ) and society's valuation of the marginal disutility of water pollution (η). The Environmental Indicators and Resource Accounting Branch of the Economic Research Service at the U.S. Department of Agriculture (USDA) has for some time been engaged in projects to develop data that can support, among other research efforts, models like TRP proposed in this paper. Given the limited illustrative objective of this part of our paper, only a brief overview of the data is provided.

Conventional output and input production accounts for each state in the 1972–93 period are derived from a panel of annual data for individual states. State-specific aggregates of output and labor, capital, and material inputs are formed as Tornqvist indexes over detailed output and input accounts. Hundreds of disaggregated farm product categories, capital asset classes, and material goods go into the construction of the output, capital, and material input indexes, respectively. Each state-specific labor index aggregates over 160 demographically cross-classified labor cohorts. A full description of the underlying data series, sources, and indexing technique is presented in Ball (1985).

The measure of S developed for this paper focuses on pesticides and their effect on ground water. (When completed, the USDA environmental indicator will be a function of both pesticides and fertilizers reaching both surface water and groundwater.) At present, the USDA has developed state- and year-specific pesticide acre-treatment (frequency of application) data adjusted for (a) the leaching potential of different applied chemicals and (b) the leaching vulnerability of soil types measured by water percolation rates for various soils.[8] These acre-treatment data are further adjusted by the authors by using data made available by the USDA. First, acre-treatments are converted to chemical pounds applied using a time series (U.S. average) of chemical pounds applied per acre-treatment. Second, data on rainfall patterns are applied across regions to convert hypothetical percolation rates to actual rates. Finally, in an attempt to model *S* in toxicity-adjusted units, pounds applied are converted to doses per pound applied using data developed at the USDA by Barnard and colleagues (1997). They define a chronic health risk dose as the quantity of chemical by weight that, if ingested daily over a specified time period, would involve serious health risk to humans. Barnard and colleagues (1997) first compute a dose equivalent for each pesticide, then aggregate over pesticides and states within regions to generate estimates by region of the total change in toxicity and persistence of farm chemicals per pound applied. The state-specific measures of chemical pounds applied just described are adjusted by these regional scalars. The resulting measure of *S* used in the following illustration represents total pesticide doses generated each year in each state's farm sector.

Application of TRP^{P} further requires an estimate of the farm sector's marginal abatement cost of improving groundwater quality by one dose. Swinand (1997) estimates a translog cost function together with input cost share equations using the preliminary panel data set described above. Marginal abatement cost (ρ) is estimated to equal $0.28 per dose. We adopt this estimate.

The model of TRP^{W} is based on marginal rates of substitution and therefore requires an estimate of the marginal social value (η) of a unit of clean (dose-free) water. Given the definition of the Barnard dose underlying the measure of *S*, η must correspond to the daily amount of water required for human consumption. Although considerable research exists attempting to estimate η, estimates found in the literature still vary considerably. Two recent survey articles (Boyle, Poe, and Berstrom 1994; Abdalla 1994) discuss various contingent valuation and avoidance cost studies found in the literature and report a wide range in valuation estimates. From both studies, the estimates of an average household's willingness to pay for clean water range from $56 to $1,154 per year. Dividing by the average 2.7 persons per household and 365 days per year, these estimates convert to $0.06 and $1.17, respectively, per daily allowance of clean (dose-free) water. Limiting attention only to those avoidance cost studies that have been published in peer-reviewed journals, the mean estimate is $428 and converts to $0.43 per unit of *S*, the value for η used in evaluating TRP^{W}.

TFP and TRP measures are reported in table 14.1 for four subperiods

8. See Kellogg, Nehring, and Grube (1998) for a full description.

Table 14.1 **An Application of TRP Measurement to the U.S. Farm Sector (average annual rates of growth)**

	1972–79	1979–85	1985–89	1989–93
Productivity growth				
TFP	0.0080	0.0274	0.0097	0.0123
TRP^P	0.0075	0.0285	0.0104	0.0129
TRP^W	0.0067	0.0294	0.0109	0.0132
Through TFP growth	0.0083	0.0277	0.0097	0.0123
Through pollution growth	−0.0016	0.0017	0.0011	0.0009
Output growth				
Market output (Y)	0.0239	0.0109	−0.0014	0.0114
Pollution (S)	0.0428	−0.1263	−0.1482	−0.2952
Value shares				
$\rho S/M$	0.0219	0.0099	0.0050	0.0020
$\eta S/(M-\eta S)$	0.0348	0.0155	0.0077	0.0030

spanning 1972–93. The TFP measure ignores the nonmarket by-product S and is derived from the conventional TFP growth accounting formula

$$\text{TFP} \equiv \frac{d\ln Y}{dT} - \sum_i \frac{w_i X_i}{M}\frac{d\ln X_i}{dT}. \tag{22}$$

The TRP^P and TRP^W measures follow directly from equations (6) and (19), respectively.

The source of the numerical differences in table 14.1 between TFP and TRP^P can be identified from a straightforward comparison of the formulas for TFP in equation (22) and TRP^P in equation (6). TFP and TRP^P differ only to the extent that the growth rates of Y and S differ—that is, only to the extent that the conventional product's environmental quality is changing over time. In the 1972–79 period, pollution growth (4.28 percent per year) exceeded conventional output growth (2.39 percent per year), implying that the environmental quality of the farm sector's product was declining during this period. As a result, reported $TRP^P < TFP$. Beginning with the 1979–85 period, however, the trend reverses. Whereas conventional output increased in two of the post-1979 subperiods and declined only slightly in one, pollution declined at average annual rates of 12.63 percent, 14.82 percent, and 29.52 percent during the 1979–85, 1985–89, and 1989–93 subperiods, respectively. After 1979, the environmental quality of farm sector output increased significantly. As a result, $TRP^P > TFP$ in each period.

The relationship between TFP and TRP^P in table 14.1 depends, as can be seen from equation (6), not only on the sign and magnitude of the relative growth rates of Y and S but also on the production sector's valuation of the pollution externality relative to the total market value of agricultural goods, $\rho S/M$. Because this value share is small in every period, exceeding 0.02 only in the 1972–79 subperiod, the resulting differential between TFP and TRP^P is small even in the post-1979 subperiods, when environmental quality of the farm product improved significantly.

Moreover, as evidenced in the table, the spread between TFP and TRP^P has decreased over time. Given that the annual rate of growth in water pollution in the later 1989–93 period (−29.52 percent) is, in absolute value, nearly seven times its growth rate in the 1972–79 period (4.28 percent), one might expect the resulting spread between TFP and TRP^P to be higher in the later period. The opposite turns out to be the case. The reason is that over the full twenty-one years of the study, water pollution declined at an average 10.6 percent annual rate. Compounded, this implies that pesticide related doses (S) reaching groundwater in 1993 equaled only about 10 percent of doses leached in 1972. Over the same period, the nominal dollar value of agricultural production (M) increased by nearly 135 percent. As a result, the sevenfold higher growth rate in S in the 1989–93 period has a weight that is only one-eleventh of its 1972–79 level. Given dramatic improvements in abatement efforts, the value weight assigned to future improvements definitionally declines.

TRP^W exhibits the same overall relationship with TFP as does TRP^P except that the difference between TFP and TRP^W is larger than the difference between TFP and TRP^P. This follows from (a) $\eta > \rho$ and (b) the differing structures of the weights on the corresponding S terms in equations (6) and (19). Even if $\eta = \rho$, the weight $\eta S/(M - \eta S)$ in equation (19) exceeds $\rho S/M$ in equation (6).

The table 14.1 decomposition of TRP^W into its two source components is informative. As expected, TFP in agriculture makes a positive contribution in every subperiod. This is not the case for the sector's contribution through changing environmental quality as modeled by the second term in equation (19). The sector's growth in pollution in the 1972–79 subperiod decreases TRP^W, whereas reductions in S after 1979 make positive contributions to TRP^W. The switch from the positive 4.28 percent growth in water pollution to the negative 12.63 percent growth rate between 1972–79 and 1979–85 highlights the importance of proper TRP accounting. Ceteris paribus, changes in farming practices added 0.33 percentage points to TRP^W growth between the 1972–79 and 1979–85 periods.

The above results are illustrative only. Not only are the results for the farm sector likely to change when the environmental indicator is fully developed at USDA, but also no attempt should be made to generalize results for the farm sector to other sectors. The magnitudes of the spreads among TFP, TRP^P, or TRP^W are expected to differ greatly across industries. After all, these differentials are functions of many things: the sign and magnitude of the change in S, the magnitudes (both absolute and relative) of η and ρ, and the relative dollar importance of pollution (ηS or ρS) to the market value of conventional output (M). Taking just the latter as an example, Repetto and colleagues (1996) find that the value share of environmental damage to GDP in agriculture (1977–91) ranged from 2 percent to 4 percent, whereas it ranged from 16 percent and 31 percent in electric power (1970–91).[9] In addition, small differences can matter. For example, if instead of the mean value of \$0.43 found in the literature, TRP^W had been estimated using \$1.17 (the value of η calculated from the maximum marginal social valuation of a unit of clean water found in the literature), average annual TRP^W in table 14.1 would have been 0.35 (instead of 0.13) percentage points below TFP in the 1972–79 period and 0.50 (instead of 0.20) percentage points above TFP in the subsequent 1979–85 subperiod. Assuming η = \$0.43, changing farm practices with respect to pesticides added 0.33 percentage points to TRP^W growth between the 1972–79 and 1979–85 periods; assuming η = \$1.17, this contribution increases to 0.85 percentage points.

The sensitivity of TRP^W to estimates of η forms a segue to one final question: How should the BLS, BEA, or any other government agency producing official productivity statistics formally incorporate measures of changing environmental quality into their productivity models? At present, given the substantial variance in estimated shadow prices, one cannot expect any agency to produce an official TRP^W estimate based on a particular value of η, one of the most politically sensitive variables in the environmental policy arena. Without consensus among researchers and policy makers, no agency can be expected to offer the appearance of endorsing a particular measure of η. However, there is an option. A distribution of TRP^W measures can be produced at the industry level based on high and low estimates of η relevant to each industry and found in the referenced literature. That strategy would not only fulfill the agencies' obligations to produce meaningful productivity statistics while responsibly protecting their credibility but, depending on the relative growth rates of the less argumentative Y and S outputs, also provide information on the time intervals and set of industries for which traditional TFP growth measures are upward- or downward-biased measures of TRP^W growth—a result that is independent of the magnitude of η (See equation [17]). The more likely outcome, however, is the politically risk-averse one: Official productivity measurement will continue to focus on conventional inputs and outputs until there is reasonable consensus on an estimate for η. As a result, if one goal of the productivity research community is to have the federal government formally incorporate environmental quality into its official productivity statistics, economists and others interested in environmental issues must narrow the existing variance in shadow price estimates. Careful data measurement and detailed industry analysis are no less important today than they were at the time of Solow's initial article.

9. See Repetto and colleagues (1996), pp. 26–39.

14.4 Concluding Comment

The model of TRP proposed in this paper has a number of desirable properties. First, although it broadens the notion of TFP growth to include nonmarket goods, it preserves the production orientation of productivity accounting. TRP, whether measured as TRP^P or TRP^W, measures productivity growth, not welfare growth. Second, zero growth in pollution is not sufficient to equate TFP with either TRP measure. TRP measures collapse to TFP if and only if producers are unconstrained by society ($\rho = 0$) *and* society derives no marginal disutility from pollution ($\eta = 0$). Third, the TRP formulations provide a natural context for evaluating the impact of regulatory policy on productivity growth. Ceteris paribus, both TRP^P and TRP^W increase in response to regulatory-induced reductions in S, and (note) even if regulation is ineffective ($\rho = 0$), growth in an undesirable by-product S enters the TRP^W formula as long as society derives negative marginal utility from $S(\eta > 0)$. Moreover, the last term in equation (21) permits a quantification of the productivity effect of a regulatory policy that is either too lenient ($\eta > \rho$) or too strict ($\eta < \rho$). As such, TRP measures enhance the role of productivity growth both as a diagnostic tool and as a barometer of the economy's success in allocating and employing its scarce resources.

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Comment William Pizer

This paper proposes the inclusion of nonmarket resource use in measures of productivity. Much as earlier work argued against labor productivity as a measure of technological change because it excluded changes in capital and materials, the authors rightly argue that the current use of total factor productivity (TFP) excludes changes in the use of valuable, though unmarketed, natural resources.

Consider the following thought experiment: Next year environmental regulations are rolled back to their pre-1970 levels. What would happen? All those resources currently going towards unmeasured (i.e., nonmarketed) environmental improvements would be converted to produce marketable output. Measures of productivity that focused solely on the use of marketed factors and output would register a positive movement. But would technology really have changed? Would welfare really have improved? The authors, myself, and, undoubtedly, many economists would say it has not.

If the general idea of counting nonmarket resources in TFP measures—a total resource productivity (TRP) measure—is not in question, the means of doing so certainly are. This is where the authors have taken an

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important step forward. While other efforts have focused on ad hoc fixes, or jumped ahead to formal models with very particular assumptions, this paper steps back and looks at the more fundamental question of what TRP should be measuring.

In particular, the authors explore two models that they characterize as production-based and welfare-based. In the production approach, an aggregate production function that includes pollution is used to derive an expression for TRP. Similarly, in the welfare approach, a social welfare function—which aggregates marketed output and pollution into a single consumption good—is used to derive an expression for TRP.

These expressions differ in two important ways: measurement of prices and, given a set of prices, actual definition of TRP. The first of these is fundamentally tied to the welfare/production distinction. However, the latter, I believe, is not.

For a nonmarket good such as pollution abatement, a key question must be the appropriate price to use in valuation. Two prices naturally come to mind—the marginal cost of abatement and the marginal benefit of abatement. The former occurs in a production-based analysis where the current technology, outputs, inputs, and level of pollution control define a marginal cost. In contrast, the latter arises in a welfare-based analysis where preferences and the current level of consumption and pollution define a marginal benefit. In a partial equilibrium framework, we are simply talking about whether to use either supply or demand curves to determine an appropriate price when the quantity is set exogenously (and presumably not where they intersect). In a general equilibrium framework, we are talking about marginal rates of transformation versus marginal rates of substitution. The choice between these two sets of prices boils down to a desire to either measure a true change in production technology or some kind of change in welfare.

A second fundamental question is how TRP ought to be measured once prices are settled upon. In other words, how do we translate changes in output, inputs, and pollution into a meaningful index measure? Based on the following definitions given in the paper (equations [6] and [19]),

$$\text{TFP growth} = (\%\text{ change in output}) - (\%\text{ change in input})$$

$$\text{TRP growth}^{\text{P}} = \text{TFP growth} + \frac{\rho S}{qY}[(\%\text{ change in } Y) - (\%\text{ change in } S)]$$

$$\text{TRP growth}^{\text{W}} = \frac{M}{M - \eta S}(\text{TFP growth}) - \frac{\eta S}{M - \eta S}(\%\text{ change in } S)$$

we can construct the following hypothetical scenarios and discuss their effect on these different measures.

In the above equations, ρ is the marginal cost of abatement, S is the amount of pollution, q is the price of output, Y is the level of output, M is consumer wealth, η is the marginal benefit of abatement, and X is the level of input.

Changes in Alternate Productivity Measures

Scenario	TFP	TRP^P	TRP^W
X, Y, S rise by 5%	0	0	< 0
Y rises by 5%	5%	$> 5\%$	$> 5\%$
Y, S rise by 5%	5%	5%	5%
X rises by 5%	−5%	−5%	$< -5\%$
X, Y rise by 5%	0	> 0	0

Certain features of TRP measurement are almost axiomatic. If technology—however defined—is not changing, TRP^P should not change. In the current model, for example, the authors assume constant returns to scale production technology in Y, S, and X. Therefore, all those variables rising proportionally does not represent a change in technology.

But what about the welfare-based metric? My intuition would be that if prices are the same, the welfare- and production-based approaches should yield the same answer. The above table indicates that is not the case. Instead, the authors have chosen to use a social production function which, by construction, leads to zero TRP growth as long as pollution is constant and the budget constraint is exactly met. The budget constraint is met as long any increase in conventional output is offset by an equal cost increase in inputs; such as, conventional TFP growth is zero. My question is the following: What does this assumption—that TRP is zero when the budget constraint is met and pollution is constant—have to do with a welfare-based view of TRP?

If, as the authors argue, both measures of TRP, "preserve the production-orientation of productivity accounting," we should be asking ourselves whether TRP is capturing changes in productivity across all production factors including pollution. In this example, an equiproportional increase in output and inputs, holding pollution constant, is clearly an improvement in the productivity of the pollution input, yet TRP^W growth is zero. Consider the analogy with capital: If a proposed TFP index measured no growth when labor and output rose proportionally (e.g., constant labor productivity) *and* capital remained constant, would this be a desirable TFP measure?

In summary, the paper is an excellent treatment of the fundamental issues surrounding the implementation of a resource-based measure of productivity. My main concern is that two important distinctions between the proposed TRP measures have been lumped together as differences between a production- and welfare-based approach. I agree with the authors regarding the distinction in prices. However, the second issue, how we define TRP for a given set of prices, seems inappropriately couched in welfare versus production terms. Based on the authors' modeling, the welfare approach results in a TRP measure with unusual properties. I believe this skirts a more important question: What happens when pollution is more closely tied to an input, such as the use of coal in energy production? Since inputs and outputs are in some sense arbitrary distinctions, a more general version of the question is how much we can bound a TRP measure by simply assuming constant returns to scale in all inputs and outputs. Then, within these bounds, can we identify some TRP measures that are more sensible than others?

Just as the switch to TFP from labor productivity generated considerable research activity and empirical work on its implementation, undoubtedly a switch to TRP will likewise create a wealth of opportunity for additional work. The authors have taken an important step in this direction.