Partial versus Total Factor Productivity Measures: An Assessment of their Strengths and Weaknesses

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ABSTRACT

A partial productivity measure relates output to a single input. Total factor productivity (or TFP) relates an index of output to a composite index of all inputs. This article reviews the strengths and weaknesses of each type of productivity measure from theoretical and methodological perspectives. Different productivity measures may be useful for different analytical purposes, and no single measure provides a complete picture of an industry's productivity performance. We argue for a balanced, context-appropriate approach to productivity analysis that incorporates both productivity measures.

Productivity measures are often used to assess a country's economic performance. There are two types of productivity measure. A partial productivity measure relates output to a single input; examples include labour productivity (output per hour worked), capital productivity (output per unit of capital), and energy productivity (output per joule of energy used). Total factor productivity (or TFP) relates an index of output to a composite index of all inputs.

In studies of long-term growth, many analysts focus on TFP as the preeminent measure of productivity. TFP growth is commonly associated with innovation and technological change, the long-run drivers of per-capita income growth. Empirically, growth accounting exercises attribute 50 to 70 per cent of cross-country per-capita income level differences to differences in TFP (Hseih and Klenow, 2010). However, TFP is subject to many challenges in terms of both theoretical interpretation and empirical measurement.

Partial productivity measures have their own set of strengths and weaknesses. Such measures are of theoretical interest because of their close relationship to factor prices. From a practical perspective, a partial productivity measure may be more informative than TFP for certain analytical purposes because partial measures allow an analyst to zero in on the efficiency of the use of specific resources that are of special interest in a particular context.

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This article assesses the strengths and weaknesses of each type of productivity measure from both theoretical and methodological perspectives. It argues for a balanced, context-appropriate approach to productivity analysis that incorporates both types of measure. The first section of the article provides technical definitions of TFP and partial productivity and outlines the relationship between them. In the second section, we discuss the strengths and weaknesses of each type of productivity measure from both a theoretical perspective and a methodological perspective. Section three concludes.

Definitions of Partial and Total Factor Productivity, and the Relationship between Them

A firm uses inputs to produce output.[2] Intuitively, the ratio of the firm's output to its input is a definition of its productivity; a firm that produces more output per unit of input is more productive. But how should 'units of input' be measured, given that there are many types of input and each is measured in different units (hours of work, hectares of land, barrels of oil, and so on)? Different choices correspond to different notions of productivity.

Let us be precise. Let $X_{1,t}, \ldots X_{N,t}$ denote the real volumes of the N inputs used by the firm at date t, and let Q_t be the firm's real output. One way of assessing the firm's productivity growth between dates $t-1$ and t is to compare the growth of Q_t to that of each of the N inputs one at a time. Let $A_{i,t} = \frac{Q_t}{X_{i,t}}$ be the partial productivity of input i. Then the partial productivity growth of input i at time t is

$$\Delta ln A_{i,t} = \Delta ln Q_t - \Delta ln X_{i,t}$$

where $\Delta ln Q_t = ln Q_t - ln Q_{t-1}$ and so on. Positive partial productivity growth for input i indicates that the firm is able to produce more output per unit of input i it uses. The most common partial productivity measure is labour productivity, which is obtained when $X_{i,t}$ corresponds to the number of hours of labour used by the firm during period t. $\Delta ln A_{i,t}$ then corresponds to growth in the firm's output per hour of labour input. In general, partial productivity can be computed for any input.

Each partial productivity measure provides an incomplete picture of the productivity with which the firm uses its inputs, and to keep track of the firm's partial productivity growth for all N inputs may be cumbersome. We may desire a single index of change in the productivity with which the firm uses all its inputs together. A reasonable way to combine the growth rates of the N inputs $X_{1,t}, \ldots X_{N,t}$ into a single composite input growth rate $\Delta ln X_t$ is to use the following index:

$$\Delta ln X_t = \sum_{i=1}^{N} \omega_{i,t} \Delta ln X_{i,t}$$

where the weight $\omega_{i,t}$ is the average share of input i in total input costs in periods $t-1$ and t.[3] Then the firm's *total factor productivity growth* is defined as

$$\Delta ln A_t = \Delta ln Q_t - \Delta ln X_t$$

Total factor productivity (TFP) growth measures changes in the amount of output the firm produces from given quantities of its full set of inputs, not just one input.

2 We will discuss productivity in terms of a firm, but in general the production unit could be an industry, a province, or a country.

3 This formula is called a Tornqvist index. The reasonableness of this approach can be defended on the grounds that the Tornqvist index is a discrete-time approximation of the ideal continuous-time index that can be derived from a production function under the assumption that an input's price is equal to its marginal product. See Hulten (2001) for a comprehensive discussion. In practice, Statistics Canada constructs volume and price measures using a different method, the chained Fisher index. It can be shown that the numerical discrepancy between Fisher and Tornqvist indexes is small.

There is a well-known relationship between the firm's TFP growth rate and its partial productivity growth rates. It is usually the case that $\sum_{i=1}^{N} \omega_{i,t} = 1$.[4] If this is true, then the expressions above can be combined to yield

$$\Delta \ln A_t = \sum_{i=1}^{N} \omega_{i,t}(\Delta \ln Q_t - \Delta \ln x_{i,t})$$

$$= \sum_{i=1}^{N} \omega_{i,t} \Delta \ln A_{i,t}$$

Thus, TFP growth is the weighted sum of the partial productivity growth rates for all the inputs, where the weights are the inputs' cost-share weights.

The expressions for TFP growth, partial productivity growth, and the relationship between them yield several insights about the various productivity measures. First, the data requirements for TFP measurement are burdensome relative to the data requirements for a given partial productivity measure. Measurement of TFP growth requires time series measures of real output, all of the real inputs used by the firm, and the nominal cost shares necessary to compute the weights. The need for data on *all* inputs can pose a problem if the firm uses some inputs that are unobserved or non-marketed. Second, the fact that the composite input X_t is a unit-free growth index implies that TFP can be measured only in growth rates; we do not have a meaningful measure of the absolute level of TFP.[5] Third, the complexity of TFP may make it difficult to explain to non-experts. By contrast, a partial productivity measure is relatively easy to compute and to explain to non-experts, and it can be measured in both levels and growth rates.

In addition to posing different practical challenges for measurement, TFP and partial productivity measures have different connections to economic theory. These points and others are discussed in the next section, which outlines the strengths and weaknesses of partial productivity measures and TFP.

Strengths and Weaknesses of the Productivity Measures

Theoretical Considerations

TFP in Economic Theory

An analyst's choices about what to measure are guided by the implications of theory about what it is important to measure. The main merit of TFP is its importance in economic growth theory. Among economists, the dominant framework for thinking about economic growth is the neoclassical growth model pioneered by Solow (1956; 1957). In that framework, TFP growth is the ultimate source of long-run economic growth.

Suppose the relationship between the firm's output Q_t and its N inputs is described by the production function

$$Q_t = F(X_{1,t}, \dots X_{N,t}; A_t)$$

Output depends on the input quantities $X_{1,t}, \dots X_{N,t}$, which are controlled by the firm, and on a scaling factor A_t that the firm takes as given. When A_t increases, the firm can produce more output for any given amount of

4 In theory, the weights sum to one if the firm's production function exhibits constant returns to scale (and input prices equal marginal products, as has already been assumed). The sum of the weights would exceed one under increasing returns to scale. In practice, the input cost shares are almost always constructed in a way that implies that they sum to one.

5 It is possible to measure the relative TFP levels of two firms (or industries or countries). Essentially, this can be done by using the above formulas but measuring the log-differences as differences between firms at a point in time rather than changes within a firm over time. We do not pursue this issue further here. See Uguccioni (2016a) for an example of relative TFP level measurement in the context of the Canadian railway industry.

inputs. Taking the total logarithmic differential of this function, and assuming that markets are competitive, we obtain

$$\frac{\dot{A}_t}{A_t} = \frac{\dot{Q}_t}{Q_t} - \sum_{i=1}^{N} \omega_{i,t} \frac{\dot{X}_{i,t}}{X_{i,t}}$$

where $\dot{A}_t/A_t$, $\dot{Q}_t/Q_t$ and $\dot{X}_{i,t}/X_{i,t}$ denote the growth rates of A_t, Q_t and $X_{i,t}$, respectively, and $\omega_{i,t}$ is the cost share of input *i* as defined earlier.[6] If we use log differences as discrete-time approximations of the instantaneous growth rates in this equation, we obtain the index number for TFP growth, ΔlnA_t, given in the previous section. Thus, the empirical TFP measure corresponds to the production function scale term in neoclassical growth theory.

Why are economists so interested in measuring the production function scale term A_t? Because in neoclassical growth theory, growth of A_t is the fundamental determinant of all per capita output growth. Hulten (1978) shows that, within this framework, aggregate TFP growth is interpretable as an outward shift in the economy's production possibilities frontier. Basu *et al.* (2013b) argue that the growth rates of TFP and of the per-capita capital stock provide, to a first order of approximation, a complete summary of changes in consumer welfare irrespective of the form of the production technology or the degree of competitiveness of product markets.

Within this framework, growth of partial productivity measures is driven by TFP growth in the long run. It is common to use the neoclassical growth accounting framework to decompose the partial productivity measure for one input into two proximate sources: TFP growth and factor deepening (that is, increases in the quantity of other inputs relative to the one input for which the productivity measure is being measured). An analyst who is firmly committed to the neoclassical theory, however, would claim that TFP growth is the only source of growth; if TFP growth were to cease, then the accumulation of producible factors would eventually stop as well. The implications of this point for assessing the 'importance' of TFP growth are discussed by Hulten (1979).

For concreteness, consider a two-input model with $Q_t = A_t F(K_t, L_t)$, where K_t is physical capital and L_t is labour. Using the accounting relationships discussed earlier, it can be shown that the growth rate of the partial productivity of labour may be expressed as

$$\Delta lnA_{L,t} = \Delta lnA_t + \omega_{K,t} \Delta ln\left(\frac{K_t}{L_t}\right)$$

The two proximate causes of labour productivity growth are TFP growth, ΔlnA_t, and capital deepening, $\Delta ln(K_t/L_t)$. But the neoclassical theory implies that the cessation of TFP growth would lead, in the long run, to the end of per-worker capital accumulation and, hence, to the end of growth in the partial productivity of labour. Thus, in a fundamental sense, it is incorrect to attribute any part of labour productivity growth to capital deepening. Capital deepening is a proximate source of labour productivity growth, but TFP growth is the only fundamental source.

The preceding discussion presents the traditional theoretical argument for focusing on TFP growth as the most important notion of productivity growth. It explains why TFP has interested economists from a theoretical perspective and why economists have been motivated to measure TFP in spite of many practical challenges. Before moving on to a detailed discussion of practical issues in pro-

6 For readers interested in the mathematical details see Murray and Sharpe (2016).

ductivity measurement, there remain five theory-based points worth noting.

Theory-dependent Interpretation

The first is that the central role of TFP in economic growth is theory-dependent. Exogenous growth in the production function scaling factor is the ultimate source of long-run growth in the basic neoclassical model. But in practice, few economists believe that the neoclassical theory provides a satisfying account of real-world economic growth. It has been acknowledged from the beginning that TFP is "a measure of our ignorance"; it is a 'black box', the residual part of output growth that we cannot yet explain (Abramovitz, 1956). Considerable subsequent research effort has aimed to explain it by building theories in which TFP growth is the endogenous result of actions taken by decision-makers.

In the endogenous growth model of Romer (1986), for example, the production function exhibits constant returns to scale in capital and labour from the perspective of an individual firm but increasing returns in the aggregate because capital accumulation produces positive externalities that firms do not take into account in their decisions.[7] One could still compute the TFP index for this economy, but it would capture the spillover effect from capital rather than (or in addition to) the growth of an exogenous production function shifter. The fundamental determinant of long-run growth is no longer exogenous TFP growth, as it is in the neoclassical model, but rather the set of parameters that govern capital investment behaviour and the positive externalities. Since TFP growth now follows capital accumulation rather than driving it, it is no longer a more fundamental measure of productivity than partial productivity measures (Sargent and Rodriguez, 2000).[8]

Sensitivity to Assumptions

The second point is that, even within the neoclassical paradigm, the interpretation of TFP (A_t) is sensitive to many assumptions including, but not limited to, assumptions about the competitiveness of markets, the rate of factor utilization, returns to scale in the production function, changes in the quality of inputs, and the manner in which technological change augments different factors of production. If factor or product markets are not competitive, if firms vary factor utilization rates over time in response to business conditions, if the production function does not exhibit constant returns to scale, if input quality changes are unmeasured, or if technological improvements augment the marginal products of different factors differently, then the clean identification of the TFP index with a production function scaling factor breaks down.[9]

Hulten (2001) provides a simple example in which capital and labour are augmented by separate exogenous scale factors. In this case, he shows that the usual TFP measure captures not only the growth rates of these scale

7 Here, 'capital' should be taken to include not only machines and buildings but also the stock of 'knowledge capital' that arises from R&D. The positive externality reflects the spillover of ideas across firms.

8 Using data from a set of OECD countries, Oulton (2016a) poses the following question: By how much would the elasticity of aggregate output with respect to aggregate capital have to exceed the capital share of output (i.e. the capital elasticity of output faced by a firm that ignores spillovers) in order for capital spillovers to fully explain measured TFP growth? He finds that in most countries, the elasticity would have to be more than twice as large as the observed capital share. He finds it implausible that spillover effects could be that large, and therefore concludes that capital spillovers alone cannot explain all of measured TFP growth. See Romer (1987) for a related analysis.

factors but also changes in the factor cost shares.

TFP Growth is Not a Measure of Technological Change

The third point is that, even leaving aside its sensitivity to assumptions, the interpretation of TFP as a measure of technical change is subtle. TFP growth is commonly equated with technological progress, but this is inappropriate. As Gordon (2016:569) emphasizes, "innovation is the ultimate source of all growth in output per worker-hour, not just the residual after capital investment is subtracted out." Many technological improvements are embedded in new forms of machinery and equipment, and firms adopt them by substituting these new types of capital for other inputs. This 'embodied' technical change is not captured in TFP (Jorgenson and Stiroh, 1999).

Moreover, even disembodied innovations (improved management practices, for example) that arise from R&D expenditures should, to the extent that the returns are captured by the investors, be included in the output and input payments of the firms that conduct the R&D. TFP grows only to the extent that the benefits of the innovation spill over to firms that did not pay for it; that is, TFP reflects only the costless component of technological change (Jorgenson and Griliches, 1967). Lipsey and Carlaw (2004) reiterate this point and show how the timing of technology diffusion and the associated output changes affect the way in which technical progress shows up in TFP indexes. Thus, the interpretation of TFP as a measure of technical progress is subject to significant caveats even if all the assumptions underlying its measurement are true.[10]

Partial Productivity Measures and Factor Prices

The fourth point is that partial productivity measures are also of theoretical interest because of their close relationship to factor prices. This is especially true of labour productivity, which has a robust theoretical connection to wages and, hence, to living standards. As noted earlier, the competitive firm will hire labour until the output elasticity of labour and the nominal output share of labour costs are equal.[11] Letting β_t denote the output elasticity of labour and w_t the real wage, this implies

$$w_t = \beta_t A_{L,t}$$

Thus, the average real wage is proportional to the partial productivity of labour, $A_{L,t}$. In the most common framework with Cobb-Douglas

9 Much of the cutting-edge research on TFP measurement focuses on disentangling these factors and isolating the technology growth component. Basu *et al.* (2006) construct a 'purified' measure of annual U.S. TFP growth that accounts for imperfect competition, variable factor utilization, input quality and non-constant returns to scale. Basu *et al.* (2013a) update the method and estimate measures of TFP growth for the consumption and investment goods sectors. Fernald (2014) provides estimates of consumption sector, investment sector, and total business sector TFP growth at a quarterly frequency, adjusted for input quality and variable factor utilization but not for non-constant returns to scale or imperfect competition (due to limitations in the availability of quarterly data). These studies attempt to strip out the factors that contaminate the usual TFP index and recover measures of the production function scale factor. The data requirements are extremely burdensome; detailed industry-level and worker-level data are needed. Moreover, additional behavioral assumptions are required in order to measure unobserved factors such as input utilization rates.

10 This may in part explain the perplexing fact that Statistics Canada's official measure of TFP (which the agency calls multifactor productivity, or MFP) has exhibited zero cumulative growth since the late 1970s in spite of the obvious fact that a substantial amount of technological change has occurred since then. The Statistics Canada MFP index for the business sector was 98.2 in 1978 and 98.3 in 2013 (from CANSIM Table 383-0021). Another part of the explanation may be measurement challenges.

11 This is equivalent to the condition that marginal revenue equals marginal cost.

technology, β_t is constant over time so that real wages are proportional to average labour productivity. This relationship (or something close to it) holds even in many models in which the TFP residual is hard to interpret. Theory therefore provides us with a reason to care about labour productivity (or partial productivity measures more generally) as well as TFP.

Interpreting Partial Productivity Measures

The final point is that certain partial productivity measures are not without their own problems in terms of theoretical interpretation. In the neoclassical growth model, for example, the capital-labour ratio grows at the same rate as labour productivity in the long run - which implies that capital productivity growth in the long run is zero. A naive analyst who observes rising labour productivity and constant capital productivity might conclude that there is some problem with the way the economy is using capital, but this would be incorrect; constant capital productivity would simply reflect the continuous accumulation of new capital at the optimal rate. Thus, care must be taken in interpreting capital productivity.

Simple models provide frameworks for organizing and interpreting data, but empirical evidence is often at odds with the models that have been referred to in this section. A first example: in Canada and across the OECD, the growth paths of average wages and labour productivity have diverged significantly in recent decades, with wages growing more slowly than labour productivity (Sharpe *et al.*, 2008; Uguccioni, 2016b; and Uguccioni and Sharpe, 2016). A second example: the basic neoclassical model implies that TFP growth drives capital deepening, but Oulton (2016b) finds no evidence of this in OECD data. In fact, he finds that higher TFP growth leads to *lower* subsequent capital accumulation.

Such theoretical puzzles may lead us to give more weight to practical considerations when deciding on the relative prominence of different productivity measures.

Practical Considerations

In practice, the choice of productivity measure should reflect the objectives of the analyst. For some purposes, a partial productivity measure may be more informative than TFP. This is especially true in the realm of environmental policy and sustainability. Energy productivity (i.e. output per unit of energy input used) may be more useful than TFP for measuring progress toward environmental policy goals, for example.[12] For policymakers interested in agricultural policy or land management issues, a measure of land productivity (i.e. output per unit of land input used) may be more useful than TFP. Given the tight connection between labour productivity and living standards, an environmentally-adjusted measure of labour productivity may be more useful than environmentally-adjusted TFP as a tool for assessing the effect of environmental damages on living standards. The general point is that partial measures allow us to zero in on the efficiency of the use of specific resources that are of special interest in a particular context.

In cases in which a partial productivity measure is preferable to TFP, an important side-benefit is that partial measures are (individually) easier to construct than TFP.[13] Careful TFP measurement requires a large amount of data - data on output and on the quantities, prices and

12 The reader is referred to the unabridged version of this article (Murray and Sharpe, 2016) for data on both partial (including energy productivity) and total factor productivity measures in natural resource industries in Canada.

quality compositions of all inputs. Diewert (2000) identifies at least nine types of input that must be measured: labour; intermediate inputs; reproducible capital; inventories; land; natural resources; working capital, money, and other financial instruments; knowledge capital; and infrastructure. The measurement of some of these elements is itself sensitive to modelling assumptions; analysts who possess the same raw data but who make different - and arguably equally defensible - methodological choices can end up with markedly different TFP estimates. In addition, the fact that the composite input measure is a unit-free growth index implies that TFP can be measured only in growth rates; we have no meaningful measure of the absolute level of TFP. By contrast, a partial productivity measure carries less burdensome data requirements, is less sensitive to controversial assumptions, and can be measured in both levels and growth rates.

The remainder of this section reviews some of the measurement challenges that arise in measuring TFP growth. Each of these challenges would also impinge on the measurement of a particular partial productivity measure; for example, difficulties in measuring capital services pose a problem for the measurement of capital productivity. But challenges associated with one input do not spill over to the measurement of partial productivity for other inputs. For TFP, by contrast, all the challenges matter.

Unmeasured and Unpriced Inputs

The fact that TFP measurement requires data on the volumes and cost shares of all inputs immediately raises two distinct but related challenges. The first is the problem of unmeasured inputs. The second is the problem of unpriced (or non-marketed) inputs.[14]

A firm's production process may depend on inputs that statistical offices do not measure. Intangible capital has been an important example of this, although official statistical offices are improving along this dimension.[15]

For another example, consider the role of bees (and the ecosystem that supports them) in the agriculture sector. Official statistical offices do not produce measures of the pollination services of bees or other services provided by the natural environment that are used as inputs in agricultural production. The exclusion of these services

13 Of course, to estimate the entire set of partial productivity measures would require most of the same data that are needed for TFP measurement. As noted above, however, researchers and policymakers often require only one partial productivity measure in order to do their work.

14 Conventional inputs, such as labour and machinery and equipment, are both measured and priced. Public infrastructure (roads, bridges, etc.) is an example of an input that is measured but usually not priced; we have measures of infrastructure, but for the most part firms do not pay a market price for the services of infrastructure. (There are sometimes fees, such as tolls or congestion taxes for the use of roads.) The services of the natural environment (e.g. the pollination services of wild bees or the water supplied by rain) constitute an example of unmeasured, unpriced inputs. We can think of no examples of inputs that are priced but unmeasured; the national accounts can in principle capture all inputs that are bought and sold on markets.

15 Intangible capital is also called knowledge-based capital or intellectual property products. According to the 2008 System of National Accounts (SNA) definition, it includes five types of asset: research and development; mineral exploration and evaluation; computer software and databases; entertainment, literary and artistic originals; and other intellectual property products (Ahmad and Schreyer, 2016). Corrado *et al.* (2005) identify a number of additional types of intangible capital, including branding and advertising, financial innovation, and innovations in organizational structure. Statistical offices differ in their treatment of the components of intangible capital. Software has long been counted in nonresidential investment, but the U.S. Bureau of Economic Analysis only began treating R&D as a form of capital investment in 2013, in response to the 2008 SNA revisions; until then, it had been treated as an intermediate input expenditure (Bureau of Economic Analysis, 2013). At Statistics Canada, research on the measurement of intangible capital and on its inclusion in the growth accounting framework is ongoing (Baldwin *et al.*, 2009; 2012).

from measured inputs means that TFP growth measures will be distorted; the part of output attributable to those unmeasured services will be attributed (incorrectly) either to other inputs or to 'technology.' The size of the distortion depends on the output elasticity of the excluded input (which determines the weight it should receive in TFP calculations) and on the extent to which the growth rate of the excluded input differs from that of the composite index of included ones.

How do unmeasured inputs affect partial productivity measures? Clearly a partial productivity measure cannot be computed for an input that is not measured. However, the absence of data on one input does not distort the measurement of the partial productivity of any other input.

The problem of unpriced inputs arises when an input has no market price. Consider the example of infrastructure such as roads and bridges. Such assets are measured as part of the stock of reproducible capital if privately owned, but much of the stock of infrastructure is publicly owned. The transportation services provided by public roads are a valuable input for firms, but firms do not pay a market price for those services. (They may sometimes pay fees, such as tolls or licensing fees.) Such prices are required in order to compute the cost-share weight on infrastructure in the composite input growth index for TFP measurement, so the fact that there is no market for infrastructure services poses a challenge. It is possible to develop econometric estimates of unobserved 'shadow prices,' but such estimates are sensitive to the methodological assumptions underlying them.

Sensitivity to Methodological Assumptions

The sensitivity of estimates to controversial methodological assumptions is a problem that extends to the measurement of other capital assets. We consider two examples. The first is the measurement of intangible capital, and the second is the measurement of physical capital services.

Consider the example of knowledge capital, a component of intangible capital. Two prices are required in order to include knowledge capital in a TFP measure: the price of R&D investment and the user cost of knowledge capital. The former is used to deflate nominal R&D expenditures into an index of real R&D investment, while the latter is used to construct the cost share weight on knowledge capital in a composite input index. TFP measurements will be sensitive to the methodological choices made by the analyst, and different choices may be defensible.

Corrado *et al*. (2005) deflated intangible capital investment by the non-farm business sector GDP deflator, while Bureau of Economic Analysis (2007) used the output deflators of R&D-intensive industries. Alternatively, prices could be estimated based on the costs of the inputs (mainly labour and materials) that were used to produce the intangible assets. In their experimental estimates of intangible capital in Canada, Baldwin *et al*. (2012) use asset-specific deflators for some components of intangible capital and follow the approach of Corrado *et al*. (2005) otherwise. User cost estimates depend on these investment prices as well as estimates of depreciation rates, relevant tax rates, and the opportunity cost of capital.

Controversial measurement assumptions also affect the measurement of capital services. Diewert and Yu (2012) estimated that TFP in the Canadian business sector grew by 1.03 per cent per year over the 1961-2011 period. Statistics Canada's official estimates showed that TFP growth over that period was 0.28 per cent per year. Gu (2012) attributed this difference to the fact that Diewert and Yu's estimate of the growth rate of capital services – at 3.0 per cent per year – was far lower than the official Statistics Canada estimate of 4.8 per cent per year. Faster measured growth of capital input, everything else being equal, implies slower measured growth of TFP. Gu traced the discrepancy in the capital services growth estimates to three main methodological differences:

- Statistics Canada estimates capital services at the industry level and then aggregates them to a business-sector estimate. Diewert and Yu compute capital services directly at the business sector level.
- In estimating the user cost of capital, Statistics Canada assumes that competitive forces equalize the nominal rate of return across assets and that the user cost includes asset-specific capital gains. Diewert and Yu assume that the real rate of return is equalized across assets and that the user cost does not include asset-specific capital gains.
- Statistics Canada uses more detailed data on capital assets than do Diewert and Yu.

A detailed discussion of these methodological differences is beyond the scope of this article.[16] The point is that there is no expert consensus that either set of assumptions is 'better' or 'worse' than the other, yet the choice matters enormously for the measurement results. Schreyer (2012) notes that the part of the TFP growth discrepancy attributable to the first bullet in the list (i.e. the choice of a top-down versus a bottom-up approach) is interpretable as an industry reallocation effect; whether one wishes to include that effect in a TFP measure depends on one's purposes. He also points out that "although user costs of capital are officially recognized in the System of National Accounts, there is no single recommendation on the details of implementation." Thus, TFP estimates can vary substantially based on the methodological preferences of the analyst constructing them.

A partial productivity measure, by contrast, depends only on a measure of output and a measure of one input. While capital productivity is affected by the challenges associated with measuring capital services, the partial productivity of other inputs is unaffected. In particular, labour productivity - the most common partial productivity measure - does not require the measurement of capital services. Labour input is easy to measure compared to capital services. This is especially true if we do not care about separating the effect of labour quality growth from other sources of labour productivity growth. In that case, we need only count aggregate hours worked as a measure of labour input.

Transparency

TFP carries burdensome data requirements, relies on complex methodological judgments about which no expert consensus exists, and has a subtle interpretation that differs from common notions of 'technical progress.' An implication of these observations is that TFP measures lack transparency and are difficult for non-experts to understand. Partial productivity measures are easier for the public to understand and relate to. Anyone can grasp the sense in which a firm has grown more productive if it produces more output per hour worked, for example. It is more difficult to explain why they should care whether output growth exceeds a cost-share weighted average of the growth rates of input volume indexes.

Challenges Affecting Both TFP and Partial Productivity Measures

Finally, it is worth pointing out two measurement challenges that affect both TFP and partial productivity measures. The first is the challenge of measuring output quality changes. The second is the issue of the comprehensiveness of the

16 Gu (2012) contains such a discussion.

output measure, especially with respect to externalities like pollution.

Output quality is said to have improved if the same physical volume of output delivers more satisfaction to consumers than it had in the past, everything else being equal.[17] Many technological changes take the form of output quality improvements. Arguably, these improvements (or at least the costless portion of them) should be included in productivity measures, but they will not be if the output measure is not adjusted to account for quality change. If the quality of a firm's output doubles but it still produces the same physical volume of output using the same physical quantities of inputs as before, productivity measures register no change even though consumers are better off. If the same welfare improvement had been achieved by doubling the physical volume of output produced with the given inputs, measured productivity would have doubled.

In order for productivity measures to capture quality change, real output must be measured in 'efficiency units' that include both physical volume and quality change. Discussions of the econometric methods that can be used to develop such estimates and the quantitative importance of unmeasured quality change for productivity measures are beyond the scope of this article.[18] In practice, statistical offices do not measure output in quality-adjusted terms except for certain goods and services (e.g. computers) for which quality change is believed to be of particular importance.[19]

The comprehensiveness of an output measure refers to its scope in terms of what is counted as output and what is not. A comprehensiveness issue of particular importance is the measurement of negative environmental externalities from production - greenhouse gases and other pollutants.[20] The level of a productivity measure may be overstated if the costs of pollution are not valued (negatively) as a part of output. The growth rate of a productivity measure may be understated (overstated) if the pollution component of output is declining (rising) over time.

The preceding discussion has stressed challenges associated with measuring and interpreting TFP. It has pointed out that partial productivity measures are often simpler to compute and easier for non-experts to interpret, and that they can provide targeted insights that a measure like TFP, based on an index of multiple inputs, misses. On the other hand, any given partial productivity measure necessarily provides an incomplete picture of overall productivity performance. Attempting to examine every partial productivity measure could lead to 'information overload,' and a single summary indicator such as TFP can be useful. Our point is not that one type of productivity measure is always and everywhere superior to the other. Both types of measure are useful in certain analytical contexts.

17 We focus on the production of consumer goods in this discussion. Aggregate output includes both consumption and capital goods. The latter are both outputs and inputs of production, so the effects of quality change in capital goods on productivity measures are subtle. An improvement in capital goods quality raises effective inputs but also raises output, and the effects on productivity are offsetting. Along the optimal growth path, the effects cancel exactly. See Hulten (2001) and the references therein.

18 Triplett (2006) provides a comprehensive overview of quality-adjustment methods.

19 Byrne *et al.* (2016) ask whether unmeasured quality change can explain the recent productivity slowdown in the U.S. and find that it cannot. They do note that unmeasured quality change may be substantial even if it does not explain a trend growth decline. Their paper includes an overview of past research on the issue. A related problem is how to account for the introduction of new goods that deliver the same services as an old good at a different rate of service flow per unit. See Nordhaus (1996).

20 The problem of comprehensiveness extends beyond environmental concerns. It is related to the longstanding critique of GDP per capita as a measure of welfare on the grounds that it excludes much (and perhaps most) of what matters for people's well-being.

Conclusion

The aim of this article is to make the case that an assessment of industry productivity trends is best carried out on the basis of a suite of productivity measures including both total factor productivity (TFP) and partial productivity measures. TFP is important because of its central role as the driver of long-run growth in the neoclassical growth model. In addition, it is useful within the neoclassical growth accounting framework because it is a source of the growth of partial productivity measures. However, TFP measurement brings a number of theoretical and practical challenges. These include:

- TFP is not a measure of technical progress, though it is often interpreted as such. At best, it measures the costless part of technical change. When various stringent assumptions do not hold, standard TFP measures capture a number of non-technological effects and these complicate its interpretation.
- The data requirements for TFP measurement are burdensome compared to those of partial productivity measurement. Unmeasured and un-marketed inputs present particular challenges.
- TFP measurement is sensitive to certain methodological choices about which there is no widespread consensus. Reasonable analysts can disagree about what methods are most appropriate, and the effect on TFP measures can be quantitatively large.
- The complexity of the methods, the subtlety of interpretation, and the fact that it can be measured in growth rates but not in levels make TFP difficult to explain to the general public compared to partial productivity measures.

Partial productivity measures are less affected by these challenges. A partial productivity measure requires less data and is less sensitive to theoretical and methodological assumptions. It can be estimated in either levels or growth rates, and it has an intuitive interpretation that non-experts can grasp with relative ease. Theory implies a direct link between partial productivity measures and factor payments; in particular, labour productivity is relevant for average wages and, hence, for living standards.

Neither TFP nor a partial productivity measure, by itself, provides a complete picture of productivity trends. TFP growth and partial productivity growth are related within the growth accounting framework, and a complete understanding of productivity growth is best achieved by examining TFP and partial productivity measures together. Moreover, particular partial productivity measures are preferable to TFP for some analytical purposes. For example, an environmental economist or policymaker might be more interested in trends in the energy intensity of production - which measures of energy productivity provide - than in trends in TFP.

References

Abramowitz, Moses (1956) "Resource and Output Trends in the United States since 1870," *American Economic Review*, Vol. 46, No. 2, pp. 5-23.

Ahmad, Nadim and Paul Schreyer (2016) “Are GDP Measures Up to the Challenges of the Digital Economy?” *International Productivity Monitor*, Number 30, Spring, pp. 4-27, http://www.csls.ca/ipm/30/ahmadandschreyer.pdf.

Baldwin, John R., Wulong Gu, Amelie Lafrance, and Ryan Macdonald (2009) “Investment in Intangible Assets in Canada: R&D, Innovation, Brand, and Mining, Oil and Gas Exploration Expenditures,” Statistics Canada Catalogue No. 15-206-X – No. 026.

Baldwin, John R., Wulong Gu, and Ryan Macdonald (2012) “Intangible Capital and Productivity Growth in Canada,” Statistics Canada Catalogue No. 15-206-X – No. 029.

Basu, Susanto, John G. Fernald, and Miles S. Kimball (2006) “Are Technology Improvements Contractionary?” *American Economic Review*, Vol. 96, No. 5, pp. 1418-1448.

Basu, Susanto, John G. Fernald, Jonas Fisher, and Miles S. Kimball (2013a) “Sector-specific Technical Change," Federal Reserve Bank of San Francisco working paper, November. http://www.frbsf.org/economic-research/files/bffk-sector-specific.pdf

Basu, Susanto, Luigi Pascali, Fabio Schiantarelli, and Luis Serven (2013b) "Productivity and the Welfare of Nations," working paper, September.

Bureau of Economic Analysis (2007) "2007 Research and Development Satellite Account," http://www.bea.gov/newsreleases/general/rd/2007/pdf/rdreport07.pdf.

Bureau of Economic Analysis (2013) "How did BEA change the treatment of spending for research and development during the 2013 comprehensive revision?" http://www.bea.gov/faq/index.cfm?faq_id=1028

Byrne, David M., John G. Fernald, and Marshall B. Reinsdorf (2016) "Does the United States Have a Productivity Slowdown or a Measurement Problem?" *Brookings Papers on Economic Activity*, Spring, pp. 109-182.

Corrado, Carol, Charles Hulten, and Daniel Sichel (2005) "Measuring Capital and Technology: An Expanded Framework," in *Measuring Capital in the New Economy*, Carol Corrado, John Haltiwanger and Daniel Sichel, eds. (Chicago: University of Chicago Press).

Diewert, W. Erwin (2000) "The Challenge of Total Factor Productivity Measurement," *International Productivity Monitor*, Number 1, Fall, pp. 45-52, http://www.csls.ca/ipm/1/diewert-e.pdf.

Diewert, W. Erwin and Emily Yu (2012) "New Estimates of Real Income and Multifactor Productivity Growth for the Canadian Business Sector, 1961-2011," *International Productivity Monitor*, Number 24, Fall, pp. 27-48, http://www.csls.ca/ipm/24/IPM-24-Diewert-Yu.pdf.

Fernald, John G. (2014) "A Quarterly, Utilization-adjusted Series on Total Factor Productivity," Federal Reserve Bank of San Francisco Working Paper No. 2012-19, April. http://www.frbsf.org/economic-research/files/wp12-19bk.pdf

Gu, Wulong (2012) "Estimating Capital Input for Measuring Business Sector Multifactor Productivity Growth in Canada: Response to Diewert and Yu," *International Productivity Monitor*, Number 24, Fall, pp. 49-62, http://www.csls.ca/ipm/24/IPM-24-Gu.pdf.

Gordon, Robert J. (2016) *The Rise and Fall of American Growth: The U.S. Standard of Living Since the Civil War*, Princeton: Princeton University Press.

Hsieh, Chang-Tai and Peter J. Klenow (2010) "Development Accounting," *American Economic Journal: Macroeconomics*, Vol. 2, No. 1, pp. 207-223.

Hulten, Charles R. (1978) "Growth Accounting with Intermediate Inputs," *Review of Economic Studies*, Vol. 45, No. 3, pp. 511-518.

Hulten, Charles R. (1979) "On the 'Importance' of Productivity Change," *American Economic Review*, Vol. 69, No. 1, pp. 126-136.

Hulten, Charles R. (2001) "Total Factor Productivity: A Short Biography," in *New Developments in Productivity Analysis*, Charles R. Hulten, Edwin R. Dean and Michael J. Harper, eds. (Chicago: University of Chicago Press).

Jorgenson, Dale W. and Zvi Griliches (1967) "The Explanation of Productivity Change," *Review of Economic Studies*, Vol. 34, pp. 249-283.

Jorgenson, Dale W. and Kevin J. Stiroh (1999) "Information Technology and Growth," *American Economic Review*, Vol. 89, No. 2, pp. 109-115.

Lipsey, Richard, and Kenneth Carlaw (2004) "Total Factor Productivity and the Measurement of Technological Change," *Canadian Journal of Economics*, Vol. 37, No. 4, pp. 1118-1150.

Murray, Alexander and Andrew Sharpe (2016) "Partial versus Total Factor Productivity Measures: Assessing Resource Use in Natural Resource Industries in Canada" CSLS Research Report 2016-20, December.

Nordhaus, William D. (1996) "Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not," in Timothy F. Bresnahan and Robert J. Gordon, eds., *The Economics of New Goods* (Chicago: University of Chicago Press).

Oulton, Nicholas (2016a) "The Mystery of TFP," *International Productivity Monitor*, No. 31, Fall, pp. 68-87, http://www.csls.ca/ipm/31/oulton.pdf.

Oulton, Nicholas (2016b) "The Mystery of TFP," LSE Centre for Macroeconomics Working Paper, forthcoming.

Romer, Paul M. (1986) "Increasing Returns and Long-run Growth," *Journal of Political Economy*, Vol. 94, pp. 1002-1037.

Romer, Paul M. (1987) "Crazy Explanations for the Productivity Slowdown," *NBER Macroeconomics Annual*, Vol. 2, pp. 163-210.

Sargent, Timothy C. and Edgard R. Rodriguez (2000) "Labour of Total Factor Productivity: Do We Need to Choose?" *International Productivity Monitor*, Number One, Fall, pp. 41-44, http://www.csls.ca/ipm/1/sargent-e.pdf.

Schreyer, Paul (2012) "Comment on 'Estimating Capital Input for Measuring Business Sector Multifactor Productivity Growth in Canada,'" *International Productivity Monitor*, Number 24, Fall, pp. 73-84, http://www.csls.ca/ipm/24/IPM-24-Schreyer.pdf.

Sharpe, Andrew, Jean-Francois Arsenault, and Peter Harrison (2008) "Why Have Real Wages Lagged Labour Productivity Growth in Canada?" *International Productivity Monitor*, No. 17, pp. 17-26, http://www.csls.ca/ipm/17/IPM-17-sharpe.pdf.

Solow, Robert M. (1956) "A Contribution to the Theory of Economic Growth," *Quarterly Journal of Economics*, Vol. 70, pp. 65-94.

Solow, Robert M. (1957) "Technical Change and the Aggregate Production Function," *Review of Economics and Statistics*, Vol. 39, pp. 312-320.

Triplett, Jack (2006) *Handbook on Hedonic Indexes and Quality Adjustments in Price Indexes: Special Application to Information Technology Products*, Paris: OECD Publishing. http://dx.doi.org/10.1787/9789264028159-en.

Uguccioni, James (2016a) "Estimating Total Factor Productivity Growth: Canadian Freight Railways, 1986 to 2009," *International Productivity Monitor*, Number 30, Spring, pp. 77-97, http://www.csls.ca/ipm/30/uguccioni.pdf.

Uguccioni, James (2016b) "Explaining the Gap Between Productivity and Median Wage Growth in Canada, 1976-2014," *International Productivity Monitor*, No. 31, Fall, 37-56, http://www.csls.ca/ipm/31/uguccioni.pdf.

Uguccioni, James and Andrew Sharpe (2016) "Decomposing the Productivity-Wage Nexus in Selected OECD Countries, 1986-2013," CSLS Research Report 2016-16, November.