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AGRICULTURAL TOTAL FACTOR PRODUCTIVITY AND THE ENVIRONMENT

A GUIDE TO EMERGING BEST PRACTICES IN MEASUREMENT

OECD FOOD, AGRICULTURE AND FISHERIES
PAPER
May 2022 **n°177**

OECD
BETTER POLICIES FOR BETTER LIVES

Agricultural Total Factor Productivity and the Environment: A Guide to Emerging Best Practices in Measurement

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Increased productivity and sustainability of the agricultural sector are core policy objectives in OECD and non-OECD countries. This *Guide* provides an overview of the current state of the art in measuring sustainable productivity of the agricultural sector and analysing sources of growth in a reliable and comparable manner across countries in a way useful for policy makers. It draws on the contributions from members of the OECD Network on Agricultural Total Factor Productivity (TFP) and the Environment that brings together relevant experts from academia and national statistical agencies. Its insights will be key for designing policies necessary to meet the triple challenge of feeding a growing world population and providing incomes to food system actors whilst ensuring environmental sustainability.

The *Guide* presents recommendations in two areas. First, on how to improve the traditional calculation of TFP based on market prices inputs and outputs, proposing harmonised methods on capital measurement, land pricing, output aggregation and quality adjustment. Second, on how to account for environmental outcomes, considering a reduction in pollution or emissions as a productivity gain, but the increased use of natural capital as a productivity loss. A main challenge is the estimation of “shadow prices” for non-market inputs and outputs. It is recommended to pursue several complementary avenues: investing in improving TFP methodologies and data; continuing investigating its expansion to include environmental outcomes; and mapping traditional TFP with other indicators of agri-environmental performance.

Key words: Agricultural productivity; Economic growth; Environmental sustainability

JEL Codes: O11, O13, O41, O47, Q1

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Key Messages

- Total Factor Productivity growth (TFP) is a key indicator of economic performance highly relevant for policy assessment. It reveals how much of the growth in production is driven by technology development and more efficient use of available technologies, and how much is driven by growth in the use of inputs.
- There is a range of potential approaches for measuring TFP growth. A growth accounting approach is practical and of particular interest for policy analysis, due to the relative ease of making calculations for multiple countries and thereby enabling cross-country comparisons.
- Recent findings using this approach suggest that there has been a slowdown in global agricultural TFP growth in recent years. Slower TFP gains imply pressure to bring more land into production and more intensive use of agro-chemicals, with related consequences for greenhouse gases (GHG) emissions, air and water quality, and biodiversity.
- Confirming and assessing more precisely the extent of the potential slowdown in productivity growth requires two kinds of improvement to existing methodologies. The first is to refine traditional calculation of TFP based on market priced inputs and outputs. The second is to account for changes in the environmental performance of the agricultural sector, accounting for non-commodity by-products. For example, a reduction in greenhouse gases emissions, if standard inputs and outputs are unchanged, should be reflected as an improvement in performance.
- The standard measurement of productivity can be improved by harmonising conventions in areas such as capital measurement, land pricing, output aggregation, input composition and quality adjustment.
- A measurement of agri-environmental sustainability performance can complete the information on traditional productivity. Furthermore, the agriculture TFP methods could be expanded to calculate environmentally adjusted productivity, building on existing work for the whole economy. Three complementary approaches are recommended to improve the measurement of agriculture TFP and environmental sustainability at the international level:
    - Test and adopt methods and results from academic work to estimate the costs and benefits of changes in environmental outcomes, and to expand the measurement of TFP adjusting for agri-environmental performance.
    - Map traditional TFP indicators onto environmental outcomes, as captured by the OECD's agri-environmental indicators.
    - Use other sources of information on productivity and sustainability, including farm level data.
- Cooperation between academics and national statistical agencies can contribute to testing empirically new methods on a large scale. The OECD can help provide robust TFP estimates that account for environmental impacts by fostering exchanges on research methods, and by proposing measurement approaches that strike a balance between technical rigour and the need to provide results to policy makers for a wide range of countries on a regular basis.

Executive Summary

Productivity is a key indicator of economic performance of the agricultural sector. Total Factor Productivity (TFP) growth captures the ability to "produce more with less": more production with a given set of inputs (land, capital, labour, materials), or the same amount of outputs using less inputs. This can be achieved either by technological change (shifts of the technology) or by changes in efficiency (the ability of a production unit to extract the maximal potential of the technology for the inputs applied). In the long run, productivity gains are a key determinant of the ability to supply adequate, nutritious food from available land, capital and labour. Increases in TFP have played an essential role in economic growth and raising farmers´ incomes. In the future, continued productivity gains will be needed to mitigate and adapt to climate change and to address other environmental challenges, while ensuring food supply.

In the context of the Sustainable Development Goals, and the objectives defined at the UN Food Systems Summit, governments face the challenges of producing more food to feed a growing global population, without depleting land and water resources, and contribute to lowering greenhouse gas (GHG) emissions. The necessary transformation of food systems that this entails will require considerable adjustments in production structures and techniques at a cost for producers and society. Technology will contribute to making these changes affordable and socially acceptable. For example, the costs of more frequent climatic stresses are continuing to increase for both producers and consumers. Without technological progress, it will be even more difficult and socially costly to cope with such shocks. If TFP growth slows, the set of policy options for adjustment will be reduced and costs will soar.

Recent findings that agricultural TFP has slowed in recent years suggest that the contribution of technological change to feeding an increasing world population might be lower in the future, putting more pressure on inputs such as land (soil health, land use), water (quality, quantity) and air quality. Such a finding deserves investigation and identification of potential causes. Traditional TFP calculations include only inputs and outputs that are priced in the market and confront methodological and data challenges. There is a need to improve indicators of TFP and make the underlying data more comparable and consistent across countries to promote further analysis of the sources of growth and to gauge a potential productivity slowdown.

Even if improvable, the methods available to measure traditional TFP are well established and already contribute to illuminate the policy debate. However, there is a need to go a step beyond traditional measures and account for changes in environmental outcomes in order to assess sustainable productivity growth. For example, a reduction in agricultural GHG emissions or any other form of pollution, holding traditional inputs and outputs constant, is a form of gaining productivity to deliver by-products that are not priced by the markets. These gains should be reflected in the measurement of the performance of the agricultural sector.

The OECD Network on Agricultural TFP and the Environment has discussed recent methodological developments and identified emerging best measurement practices that have recently been brought together into the publication *Insights into the Measurement of Agricultural Total Factor Productivity and the Environment*. This book covers many technical issues, from the use of simple indicators based on the growth accounting approach, to the need for investment in shared databases. Coordination efforts and the development of similar conventions and data across countries are particularly needed in the measurement of capital (e.g. depreciation patterns and service life); in the pricing of land; in adjusting for quality and new products for outputs and inputs (e.g. chemicals); and in aggregating over different outputs.

The other major area of work by the OECD Network on Agricultural TFP and the Environment concerns how to incorporate the costs and benefits of the environmental impacts of agriculture as part of a wider consideration of the environmental and economic performance of the sector, that is, its sustainable productivity growth. Academic research has made a substantial contribution to this area. There are now several promising ways to account for undesirable, as well as desirable, by-products and inputs that are not priced by markets, and developing TFP indicators that encompass both marketed outputs and environmental inputs and outputs. If agriculture increases the production of public goods such as ecosystem services and biodiversity, again holding constant traditional outputs and inputs, this would then appear as productivity gain. Conversely, an increase in the consumption of natural capital such as aquifers, and soil integrity should appear negatively in a TFP indicator, even though these goods are currently not priced by markets. An increase in emissions of undesirable by-products like nitrogen or pesticides run-offs should also be considered as a fall in TFP, even when traditional inputs and outputs are unchanged.

Academic research has focused on methods that ensure that TFP measures adjusted for environmental by-products give theoretically consistent indicators. So far, this has led to measurement methods at odds with the need for simple and transparent indicators. Furthermore, the robustness and consistent interpretation of these results are still to be tested, which requires robust databases with production (and environmental) accounts. This raises difficulties in terms of ensuring routine implementation of environmentally adjusted TFP indicators by national statisticians. However, some of the recent methods developed in academic research can provide useful input to statistical agencies. This is particularly the case for improved estimates of “shadow prices” for non-priced, non-commodity goods, which could be used in measuring sustainability and developing more easily implementable comprehensive TFP. There is a need to improve cooperation between academics and nationally statistical agencies to test and compare results of these efforts across countries.

Given the current state of the art and the difficulty to capture policy linkages, it is recommended to pursue several complementary avenues to make progress in measuring sustainable productivity growth. There are several available options. Exploring and improving traditional TFP methodologies by including by-products and natural resource inputs with appropriate shadow prices is one option. A promising alternative is to map traditional TFP indicators onto environmental outcomes, as captured by the OECD’s agri-environmental indicators. Policy analyses and measurement of sustainable productivity growth can be based on performance indicators that complement or combine productivity measures with sustainability indicators. The use of farm level analysis and indicators is a further complement to traditional TFP measures for a comprehensive appraisal of sectoral performance.

1. Issues and challenges

Increasing productivity is essentially about producing more with less: more production with a given set of inputs (land, capital, labour, materials), or the same amount of outputs using less inputs. It reflects technological change and technical efficiency improvements that directly contribute to feeding an increasing world population, while avoiding more pressure on natural resources such as land, water and air. Therefore, it is an important way to ensure global food security and provide livelihoods to those working in the sector in an environmentally sustainable manner. Agricultural productivity is a main indicator of the sectoral performance, and its measurement and interpretation are challenging for both researchers and policy makers. The first challenge is to measure agricultural productivity performance accurately for international comparisons. The second challenge is accounting for the sector's use of natural resources and its environmental performance. Finally, a third challenge is to make this measurement useful for policy assessment and analysis. Section 1 provides and overview of these issues and challenges and how to respond to them. Sections 2 and 3 provide a technical overview of recommendations to improve the measurement of TFP: the traditional measurement based only on market priced inputs and outputs; and its expansion to include environmental outcomes. Section 4 provides a way forward with a special focus on the potential role of the OECD.

The OECD has developed the concept of Environmentally Adjusted Multifactor Productivity (EAMFP) in analyses for the global economy (Cárdenas Rodríguez, Haščič and Souchier, 2018[1]; Schreyer, 2019[2]). Since 2017, the OECD Network on Agricultural TFP and the Environment has gathered a set of experts to share experiences and best practices on measuring agricultural TFP and applying a similar environmental adjustment method the sector. *Insights into the Measurement of Agricultural Total Factor Productivity and the Environment,* hereafter *"Insights"* (OECD, 2022[3]) brings together the proceedings of these discussions dealing with the most advanced methods.

The *Insights* publication provides some examples and identifies some promising methods to improve TFP measurement and to adjust it to incorporate environmental outcomes. Recent developments in academic research make it possible to adjust standard TFP measures for changes in desirable by-products (public goods), undesirable by-products (pollution) and depletion of natural capital. However, obstacles remain to defining the price of non-market inputs and outputs and to calculating a simple sustainable TFP index. The robustness of the results of specific applications to expand the TFP method to include some environmental outcomes still have to be tested.

The traditional TFP measure is already a very useful tool for understanding the nature of technical changes and potential policy levers. Incorporating environmental sustainability into the productivity discussion is a policy imperative that can be achieved by bringing together different methods and data sources.

Why is TFP important?

"Productivity growth is probably the single most important indicator of an economy's health: it drives real incomes, inflation, interest rates, profits and share prices". This quote from *The Economist* (4 November 2004) sums up the importance of technical change and productivity gains in all aspects of economic theory and policy.

Produce more with less

For micro-economists, TFP is the ratio of an aggregate of the quantities of goods and services produced (outputs) to an aggregate of all the factors used to produce them (inputs). The productivity gains of a particular production unit (firm, country) include technological progress and technical efficiency gains.[1] Technical progress is linked to the discovery of new production methods, and corresponds to a shift in the "frontier" which represents the best production technique available, given the state of science and technology. This shift is generally a result of research and development (R&D), its dissemination and adoption. Technical progress pushes the frontier of best techniques.

Technical efficiency corresponds to the greater or lesser proximity of the individual production unit to this (common) frontier. A gain in efficiency is reflected in a firm or country moving closer to this frontier of best available practices, for example through the adoption of better techniques or management.

Taking a simple identity as a starting point, one can easily show that production growth is the sum of two rates of growth: that of TFP and that of input used.[2] Applied to the agricultural sector, this decomposition shows that the availability of agro-food goods per capita can be explained, historically, by a growth in cultivated land, applied fertilisers, labour force, etc., and by the growth of TFP. In brief, TFP growth is the residual of the output growth that cannot be explained by the growth in the quantity and quality of the different inputs used.

TFP growth, whether it corresponds to technical progress that pushes the frontier of best techniques, or to the production unit getting closer to the best technique, will result in lower unit production costs. When new technologies improve the best possible techniques, and when firms improve their efficiency by adopting them, the result is more production for less inputs, which means more value creation, better returns to inputs, and a more competitive sector.

Increase the standard of living

For macroeconomists, technical progress is the essential determinant of growth, which in turn is the key to generating and distributing extra real income and employment. Technical progress is essential for economic growth to be sustainable. Indeed, in the long run, productivity growth is the key for continued output growth per worker. Productivity gains also allow a decrease in real prices, which translates into higher real per capita incomes.

Thus, TFP is important for raising living standards, for employment and for the ability to finance the State and public goods and to reallocate resources across sectors. Productivity improvements can also be important in addressing social goals, including environmental problems, while improving standards of living.

The total factor productivity of the agricultural sector is calculated as a ratio between the outputs and inputs produced and used in that sector. Technical progress is about new methods to combine the inputs to produce the agricultural outputs. Technical efficiency in agriculture is about how an individual production unit can move closer to the common technology frontier. Both technical progress and technical efficiency contribute to agricultural TFP growth.[3] A result of TFP gains over the last decades is that agricultural

[1] In this simplified presentation, we refer to disembodied technical change, this is, technical change that is not captured in the measures of the individual inputs (e.g. capital, for example machinery and equipment). In theory, technical change embodied in the different inputs is capture by the input measures (e.g. capital) and not by TFP.

[2] See Chapter 2 of the Insights book.

[3] Another important factor captured by TFP is economies of scale (see OECD (2001[8]). Innovations in agriculture have also been a response about how to exploit further potential economies of scale in agriculture.

production has grown beyond population growth and the living standards and working conditions of many farmers have improved.

Different paths of agricultural productivity growth

In agriculture, the search for productivity gains is often seen as the search for higher yields, which is associated with mechanisation, increased use of fertilisers and chemicals and which can result in a degradation of the environment and working conditions. This vision reflects a blurred distinction between technical progress and technical efficiency gains, and a particular path of improvement in productivity through a factor substitution that replaces labour by materials or machinery. Nevertheless, increased use of materials such as agrochemicals has often accompanied changes in technology, partly because the price of these materials does not fully internalise the negative external effects. This has often resulted in environmental pollution. But this is just one possible path of productivity growth.

In contrast, increased productivity can contribute to reducing the GHG emissions intensity of agricultural output.[4] Following the same principle of producing more with less, increases in productivity can be achieved through greater efficiency and potentially less reliance on natural resources, contributing to reducing the negative environmental footprint of the sector. Innovation and technological change can respond to agri-environmental challenges and provide a sustainable path of productivity growth.

While there are indeed some linkages between the evolution of agricultural productivity and the degradation of natural capital over the last decades, the cause should not be confused with the effect. For the biosphere to be maintained in the coming years, adjustments of agricultural production methods, prices and public policies must be made. However, a high rate of technical progress is necessary to make new methods available and prevent this adjustment from being too costly and socially unacceptable. For example, the costs of agriculture being exposed to more frequent climatic stresses continue to increase for the entire community. Innovations in agronomy and production technologies are necessary to absorb such shocks. Without technical progress, it will be difficult and socially costly to cope with the scarcity of resources and the effects of global warming. In brief, if TFP slows down, the set of possible policies for adjustment will be reduced.

More generally, just as improved TFP has so far played an essential role in economic growth, it can play a major role in the mitigation of, and in adaptation to, climate change in the future. Should technical progress slow or miss the sustainability goals, agricultural production cannot keep pace with the growth in population, while reducing its negative impacts on the environment (OECD, 2021[4]). Although solutions to current climate and environmental crises cannot be purely technical, a decline in the growth of TFP or a productivity path that does not explicitly respond to existing environmental pressures would make the transition more difficult.

Need to adjust productivity measures for environmental impacts

Traditional TFP measures only consider marketed inputs and outputs. They do not account for GHG emissions or other social or environmental effects. Today, given the demands for environmental sustainability, the traditional measurement of productivity needs to be complemented with an assessment of the sectoral environmental performance. The option followed by the OECD Network on Agricultural TFP and the Environment (OECD, 2022[3]) is to review TFP measures so that they take into account this impact on natural capital and polluting outputs.

[4] An example is genetic improvement in dairy production which requires a smaller number of methane emitting animals for a given production; or new feeding technologies and complements that reduce emissions per ton of dairy products. Techniques that inject urea or other nitrogen fertilisers in soil can also result in lower ammonia emissions.

What can we learn from TFP analysis?

The primary goals of TFP measurement are to analyse the determinants of production growth over time and to identify the sources of economic growth. Measuring TFP is a first step for understanding the sources of productivity increases and investigating ways of fostering economic growth. Partial Factor Productivity (PFP) complements this information by identifying different productivity pathways (Box 1). The path breaking work of Griliches in the 1960s identified the main sources of conventionally measured productivity in US agriculture, such as improvement in the quality of labour through education, genetic improvement in crops and livestock, and economies of scale. He also highlighted the role of agricultural research and extension, as well as measuring the social rate of returns of public funds allocated to agricultural research.

Box 1. Partial and Total Factor Productivity

Total factor productivity is the ratio of an aggregate of output quantities to an aggregate of quantities of all inputs. The aggregate is constructed using an index number, i.e. a formula that consists in a weighted sum of quantities. Prices or rates of return are usually used as weights to aggregate quantities of outputs and inputs. TFP differs from partial productivities, defined as the ratio between agricultural output and one particular type of input, e.g. the yield (partial productivity of land), the productivity of capital, the productivity of labour and that of intermediate inputs. It is noteworthy, for example, that macroeconomists often rely on “labour productivity”. In agriculture, partial productivities give a useful picture of what has happened in the sector over time, but they need to be considered together. Indeed, a partial productivity may capture technical progress but also factor substitutions. While technical progress relates to shifts of a technical frontier, partial productivities also capture shifts along and towards the frontier.

TFP and partial factor productivities (PFPs) make it possible to distinguish the different phenomena behind the evolution of agricultural production. For example, between 1948 and 1985 agriculture in the United States more than doubled the use of capital (equipment), while the volume of agricultural labour fell by two-thirds and the use of intermediary inputs increased by 77%. Over the same period, the volume of production almost doubled (USDA, 2021[5]). The result is a partial productivity of labour, which has increased sharply, in part due to factor substitutions and technical efficiencies, but also due to technical progress, with TFP more than doubling in the same period. TFP makes it possible to decompose this evolution. The PFPs provide additional information to interpret the nature of the productivity changes and their embodiment in certain inputs (capital, labour, intermediary…).

Measuring and identifying the sources of growth

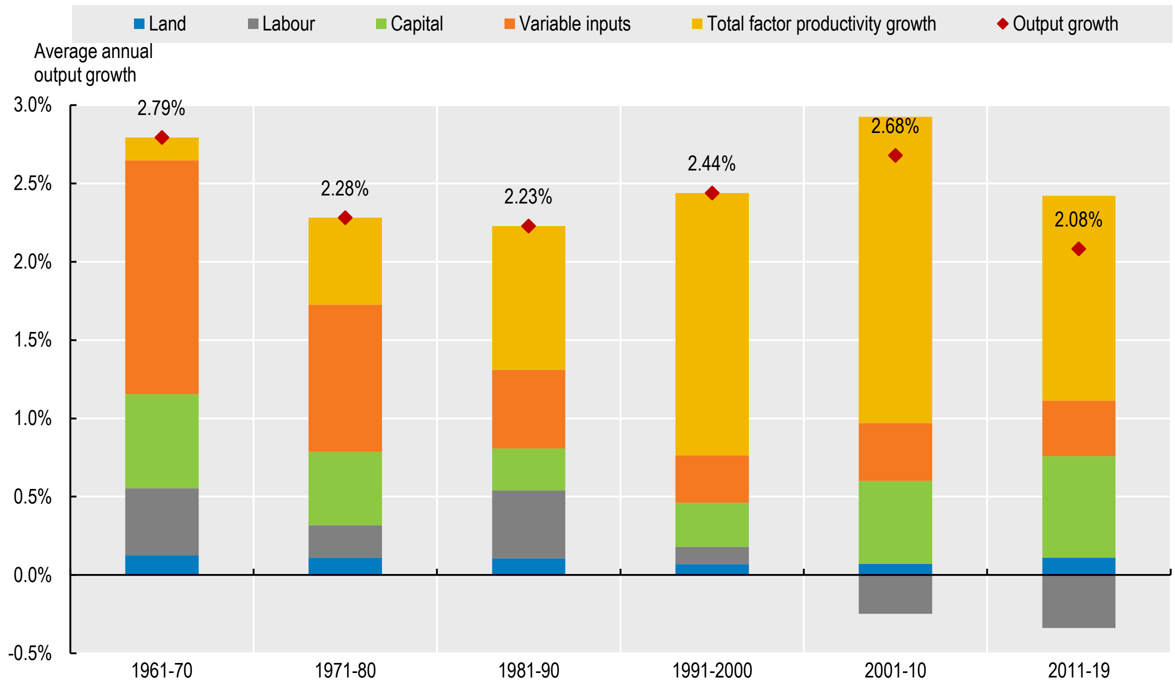
In practice, the example of the United States shows that the total aggregate input volume has changed very little since the Second World War; only its composition has changed, with more intermediary inputs and less labour. The growth in agricultural production per capita thus corresponds mainly to total productivity gains. The same is observed in countries where there has not been a strong increase in cultivated areas over the period, which is the case in most OECD countries. There are precise estimates of TFP in the agricultural sector over a long period in Australia or Canada, and they give results close to those described for the United States. Therefore, total factor productivity gains explain most of the growth in production observed, rather than an expansion of aggregate inputs.

At the global level, productivity gains are behind the failure of Malthus' predictions of decreasing per capita food supplies to materialise. There is no assurance, however, that such gains will continue in the future, nor that they will be shared globally. This will depend on training, research and development efforts, but also on the quality of institutions, and the dissemination and adoption of knowledge and market conditions.

Degradation of natural capital, in particular soil and aquifers, as well as climate change, could limit agricultural production in many countries. It is uncertain whether productivity gains (themselves potentially hampered by such changes) will be enough to compensate for such degradation.

The International Agricultural Productivity Database (USDA, 2021[5]) produced by the USDA Economic Research Service makes it possible to decompose the growth of world production into the contribution of different factors in total costs (land, labour, capital and variable inputs, and the residual TFP growth (Figure 1). This database relies on data from FAO and allows TFP growth comparisons across countries worldwide. Results suggest that there was only a small growth in productivity in the 1960s, accounting for around 0.1% of annual growth, with production driven by the use of additional inputs including capital, land and intermediary inputs. Productivity growth strongly increased in subsequent decades, reaching up to 1.9% in the 2000s. However TFP growth slowed in the last decade of the 2010s (Figure 1). The EU Commission also finds lower TFP growth in the case of the European Union, United States and Australia over the recent period (EU Commission, 2020[6]).

Figure 1. Measured World TFP growth slowdown since the early 2000s



Source: USDA (2021[5]).

Should we worry about the slowdown of TFP gains?

If this TFP growth slowdown is accurate, the consequences could be globally significant in terms of higher food prices, and food insecurity. With lower productivity growth, the ability to adapt to population growth or climate change is more limited. Lower productivity gains will also put pressure on resource use, making it necessary to increase cultivated area, with negative implications for biodiversity and deforestation.

Should the slowdown of global agricultural productivity gains observed by USDA (2021) be confirmed, it could be linked to several causes. Climate change and more frequent extreme events have been put forward, as well as the development and spread of new diseases and pathogens. The slowing pace of innovation or the inefficient dissemination of research results and innovation could also be part of the problem. Loss of momentum in agricultural policy reforms may also have played a role, along with other policy or institutional modifications. Further analyses will allow these hypotheses to be rigorously tested and to identify potential solutions. However, this analysis first requires a comprehensive measurement of TFP growth.

Environmental sustainability as main challenge in measuring productivity

The value of measuring TFP is clear. However, the practical difficulties of constructing reliable indicators can reduce their usefulness to policy makers. The need to resort to strong assumptions, as well as the difficulties of obtaining harmonised data, undoubtedly explain a certain scepticism in the face of these measures. TFP is not an indicator that policy makers put at the top of the list of their information priorities. As a result, the impact of this indicator on public policy discussions remains well below that which economists would prefer. This scepticism is amplified by the difficulty of integrating the consumption of natural capital and undesirable by-products, such as pollution, into TFP indicators.

Three main challenges: First, simplicity

The first challenge for TFP measurement is making simple and operational but still rigorous indicators. The economic theory of index numbers has made it possible to have reliable approximations. Growth accounting approaches can identify the contributions of the various determinants of productivity gains but require some restrictive assumptions.

Considerable progress has been made on unravelling technical progress and variations in technical efficiency. Such measurements can rely on econometric estimations of general production functions or other representations of the technology. The concept of "distance function" also allows for a general framework, which encompasses many rigorous ways to represent the technology (Section 2). There are sophisticated estimation methods for TFP indices, using econometric (stochastic frontiers) or non-parametric (Data Envelopment Analysis) methods.

28. However, while advances have been remarkable over the past twenty years in the academic world, more can be done to ensure the robustness of some of these econometric methods and the simplicity of their interpretation. In particular, using these for international comparisons requires simple indicators based on information that is available in the different countries. Index numbers are particularly appropriate for the regular publication and update of productivity statistics and, therefore, they are very convenient for implementation by national statistics offices (OECD, 2001[7]).

Second, harmonised data

The second challenge for measuring TFP is the need for coherent data over time and among countries. The national economic and agricultural economic accounts (only available in selected Member states on a harmonised basis) are the main data sources. Major conceptual and technical developments have improved measurement, for example, by making it possible to account for changes in the quality of inputs and outputs, by integrating variations in the use of available capacities of land, labour and capital. However, their implementation requires coherent data between OECD countries, which is currently not the case. Government agencies have invested in the construction of such sources, with the *OECD Measuring Productivity Manual* (OECD, 2001[8]) acting as a worldwide reference.

Third, valuing non-market inputs and outputs

The third major challenge in measuring TFP is that official TFP measures only account for marketed inputs and outputs. By neglecting "free" inputs such as air, climate, and often water, it is implicitly assumed that these goods are not scarce and therefore can be renewed indefinitely and without cost. Similarly, by neglecting bad outputs such as pollution, it is implicitly assumed that they can be indefinitely emitted. This is not a legitimate assumption while evidence is mounting on the overexploitation and scarcity of several forms of natural capital. The challenges of simplicity and harmonised data are cumulative to this third challenge of adding the environmental sustainability dimension to the traditional productivity measurement.

Improving the measurement of environmental inputs and outputs is crucial

Until recently, the production of non-commodity outputs, which include desirable by-products (public goods, see Box 4) and undesirable by-products (pollution), have been ignored in traditional TFP measures. TFP indicators that do not account for non-commodity inputs and outputs give a biased picture of the evolution of technology, for example by ignoring the effects of agriculture on the environment. In particular, certain forms of production use resources that are free but not renewable or beyond the capacity for renewal. This results in TFP indicators that omit inputs that should logically be included. If output growth was accompanied by a degradation of natural capital, and which was not counted as an input, TFP growth might have been overstated. The measurement will also be biased if, for example, the investment in pollution control equipment to prevent leakage of ammonia in the air is counted as input and the reduction in pollution is not counted at all. Understandably, performance indicators that do not account for the destruction of natural capital and other environmental impacts of farming are unlikely to be seen as credible. In short, productivity discussions and indicators can no longer limit themselves to consider only marketed inputs and outputs.

The OECD, for several years, has developed the concept of Environmentally Adjusted Multifactor Productivity[5] (EAMFP) in analyses for the global economy (Cárdenas Rodríguez, Haščič and Souchier, 2018[1]; Schreyer, 2019[2]). In order to use this framework in the case of pollution, the idea is to consider not just the growth of GDP but also the abatement costs of this pollution. The general mechanism of this adjustment is currently limited to a few pollutants and fossil fuel extraction activities (Box 2). A challenge is to broaden these concepts for agricultural TFP, by mobilising data on water, soil, forests, fishery resources and biodiversity, and sector-specific pollution such as ammonia and nitrogen leakages. Section 3 gives directions for making these adjustments, while recognising that the full inclusion of environmental goods in agricultural TFP indicators still faces limitations.

[5] Multifactor productivity (MFP) and total factor productivity (TFP) are equivalent in this discussion. In both cases, the aim is to cover all relevant inputs in the calculation of productivity.

Box 2. OECD adjustment of TFP for environment for the whole economy

When measuring productivity for the whole economy, the OECD has proposed to adjust the traditional TFP measure to account for environmental issues, in particular the depletion of natural assets, and the emission of pollutants. The OECD has defined the Environmentally Adjusted Multifactor Productivity, or EAMFP (Cárdenas Rodríguez, Haščič and Souchier, 2018[1]):

> EAMFP = GDP growth + Adjustment for pollution abatement – contribution of labour – contribution of capital – contribution of natural capital.

Substituting the traditional decomposition:

> TFP = GDP growth – contribution of labour – contribution of capital

Showing that, contribution of natural capital

> EAMFP = TFP – Adjustment for pollution abatement – Growth contribution of natural capital.

Note that the EAMFP is lower than the traditional TFP if there is an increase in the use of natural capital or an increase in the flow of pollution with respect the previous period. In these cases, the traditional TFP growth had been overstated. These adjustments correspond to the contribution of natural resource inputs and pollution and measures the change on the intensity of the flow of use of these natural resources, not the change in the level of capital stock. For some important environmental policy issues as climate change, the level of the stock (the stock of GHG emissions in the atmosphere) can be as relevant as the intensity of its use (the flow of GHG emissions).

To calculate this adjustment, the OECD has gathered data on 46 countries, including all OECD countries since 1991 on natural assets, including fossil fuels (oil, gas, coal) and a number of pollutants The prices estimated and used for these calculations are the shadow price for producers (the user cost of natural capital and the marginal cost of abating pollution). The difference between EAMFP and TFP is larger for countries whose economy rely heavily on the extraction of natural resources (e.g. Russian Federation, Saudi Arabia, and to a lesser extent OECD countries such as Chile or Norway) or experience a significant correction of their GDP for pollution abatement (e.g. Korea and Mexico).

Clearly, there is a need to improve the method (use of elasticities of GDP with respect to pollution) and data (coverage of natural resources, monetary valuation). Empirical work, such as the one conducted by Statistics Canada, shows that inclusion of undesirable outputs reduced productivity growth relative to standard measures, as growth in bad outputs are subtracted from good outputs to derive total output measure (Gu, Hussain and Willox, 2019[9]).

Other avenues to assess sustainable productivity

Other approaches to combine productivity and sustainability have been explored by the OECD and others. The OECD's Farm Level Analysis Network has worked to measure productivity and environmental sustainability among farms in selected countries (Sauer and Moreddu, 2020[10]; Antón and Sauer, 2021[11]). This approach uses farm level data to measure indices of farm total factor productivity and sustainability and combines them to classify farms into groups according to their performance. The agricultural sector typically includes both well and poorly performing farms that as a whole determine the overall productivity performance of the sector. This type of analysis provides insights on the drivers of performance and of the dynamic adjustment of farms in terms of technical change and efficiency. It has the advantage of providing more granularity on farms and specific production systems, but it has its shortcoming in terms of interpretation for country benchmarking, potential divergence between local and broader sustainability and of the limited availability of environmental performance information in farm surveys.

The OECD has built over the years the agri-environmental indicators database[6] to enable measurement of the environmental performance of agriculture across OECD countries. This database includes indicators on agricultural land, ammonia, energy use, farm birds, GHG emission, nitrogen balance, pesticides, phosphorus balance, soil erosion and water. Some of these indicators have been combined to measure agri-environmental performance indices that allow country benchmarking. Furthermore, different degrees of substitution between productivity and sustainability performance were assumed to build possible combined indicators of weaker or stronger sustainable productivity growth.[7] This approach has the advantage of having more flexibility to build different indicators that focus on different agri-environmental indicators and on alternative sustainability concepts such as absolute levels versus intensity.

These and other alternative approaches to measure sustainable productivity growth deserve to be explored with investments in data, methods and analysis to make sure that the different aspects of sustainable productivity are brought to the policy debate (Section 3).

How to improve traditional TFP measures?

Measurement of total factor productivity (TFP) is a long-standing area of policy interest. TFP for the aggregate agricultural sector is potentially one of the key policy performance indicators. Our knowledge across countries is far from perfect, but available empirical evidence on traditional TFP measures is converging despite the heterogeneity of data and methods employed (Section 2).

There is a basic consensus on how to measure TFP

There is now a relative consensus on the basic approach to traditional TFP measurement. National and international agencies are recommended to use an index and growth accounting approach that is simple to calculate and interpret. The main difficulties for coherent and comparable approaches between OECD countries, and for international comparisons, lie in the differences between data sources. The OECD Network on Agricultural TFP and the Environment could help to harmonise data and methods across countries.

But a need to support the development of cross-country databases…

For cross-country comparisons of TFP gains, including non-OECD countries, the database compiled by the Economic Research Service of the USDA could be at the core of a common effort (Fuglie and Rada, 2015[12]). The resulting TFP measures rely on a common set of information from FAO. That said, the need to work with representative inputs and cost shares and to have one single category of labour rules out many of the refinements that have been recommended by the experts (Shumway et al., 2017[13]) as included in the *Insights*. However, the USDA-ERS database provides a precious starting point that could be complemented with additional sources of information (see Chapter 2 of the *Insights* (OECD, 2022[3]).

[6] See https://www.oecd-ilibrary.org/sites/4edcd747-en/index.html?itemId=/content/publication/4edcd747-en.

[7] See Box 1.6 in Chapter 1 of OECD (2021[21]) and Chapter 6 of OECD (2021[52]). These indicators are based on weak, strong and semi-strong sustainable productivity growth indicators in (Lankoski and Thiem, 2020[50]).

…or harmonisation efforts for international comparisons…

Rather than including all countries in a common dataset, another avenue is to make national TFP estimates more alike by adopting a consistent approach across national agencies. A practical first step is to harmonise the way capital inputs are measured. The approach developed for agriculture by Ball et al (1993[14]) could be used with comparable coefficients across countries. The OECD Network framework seems particularly useful for compiling a harmonised database on these parameters, and bringing together a panel of experts to assess whether the different conventions used by statisticians in OECD countries may need to be adjusted.

Accounting for land quality and changes in the composition of output or variable inputs can also be harmonised. Australian and Canadian agencies have already adopted conventions used by the USDA for pricing land and accounting for the changes in the composition of pesticides and fertilisers. Again, common procedures for gathering the relevant data for land and labour could be defined to account for quality differences, capacity utilisation and user costs. There is a need to consolidate the information needed to construct hedonic prices for land or pesticides, building on the experience of the USDA and other national agencies. For all these issues, farm level data could also be of great help.

…and to promote and disseminate TFP analysis for policy advice

Understanding TFP enriches the discussions on policy options. Because technical progress will play a crucial role in making adjustment to new challenges such as global warming and water scarcity, it is important to identify and characterise any potential TFP slowdown and to decompose the sources of changes in agricultural output, including the reductions and increases in different inputs such as labour, capital, land or fertilisers. This could help identify different pathways for productivity growth and allow investigation of their different implications for incomes, food security and environmental sustainability.

TFP analysis can enlighten other policy debates beyond productivity

The work on TFP could inform other types of analyses, particularly relevant for stakeholders. For instance, an important co-product of the work carried out by the OECD Network on Agricultural TFP and the Environment is the work on prices. Too often, prices have been only used to aggregate quantities in TFP indices, or to deflate series. However, prices have a considerable interest for policy analyses. For example, the data compiled for TFP measurement could provide the source for spatial (cross-country) deflators, otherwise called Purchasing Power Parities. While these PPPs are well known in macroeconomics, PPPs specific to inputs can help compare the differences, say, in production costs, and identify what comes from productivity differences and what comes from input cost advantages (see Bureau, Butault and Hoque (1992[15]) for an application to EU-US cost of production of major agricultural commodities).

Finally, while TFP analyses have often focused on growth accounting, it could be useful also to study the distribution of productivity gains. Typically, in agriculture, only part of the TFP gains are kept by farmers (the “treadmill” effect). That is, farmers need to innovate to stay in business, but competitive pressures force them to pass productivity gains downstream (to industry or consumers) or upstream, or to the owners of fixed assets (landowners, quota owners). Methods of “surplus accounting” derived from Kendrick and Sato (1963[16]) and formalised by Courbis and Templé (1975[17]) make it possible to quantify the “productivity surplus” (i.e. the value of extra output generated by TFP) over a period of time and to study how this surplus is shared by the various economic agents along the supply chain through changes in input prices, output prices and farmers’ incomes. The source and distribution of TFP gains, through price and quantity changes over time, could be a useful addition to the analysis of generation of TFP gains, and help link the TFP work to the Monitoring of agricultural policies in a tighter way.

How to calculate environmentally adjusted productivity growth?

An important drawback of conventional productivity measures is that they only account for those inputs and outputs for which there are observable market transactions, while by-products that result from agricultural activity and, in general, the role of the environment in production – both the use of natural capital and the abatement of pollution – are not taken into account. This omission can be a serious source of systematic bias in productivity calculations and the interpretation of the results, leading to incorrect policy conclusions if the drivers of growth and productivity are badly identified (Section 3).

The agricultural sector has stewardship responsibility to preserve natural capital and to contain, even reduce, pollution costs that for society are considerable. Current levels of methane and nitrous oxide emissions, nitrogen, phosphorus and pesticides run offs and leaching, and biodiversity erosion exceed sustainability limits. On such issues, national and international commitments have been made, often with precise targets. A performance indicator for the sector that ignores such objectives has serious limitations in informing policymaking.

OECD has developed knowledge on how to measure environmentally adjusted productivity …

The main challenge is to incorporate in the policy discussion on performance not only the efficient use of market inputs and outputs, but also the more efficient use of natural capital and the reduction of pollution. Without these latter considerations, it is not possible to have a good understanding of the overall performance of the sector. The OECD has knowledge and methods for measurement of economy wide productivity growth (OECD, 2001[8])and its adjustment for environmental outcomes (Cárdenas Rodríguez, Haščič and Souchier, 2018[1]).

This approach adjusts TFP calculations by expanding the inputs or outputs considered beyond those that are traded in markets, in particular to include pollution. The OECD Environment Directorate has defined Environmentally Adjusted Multifactor Productivity for the whole economy (Box 2), which accounts for a set of environmental externalities. Adjusting agricultural TFP measures in this manner is also possible. The *Insights* summarises the findings of the Network on including environmental issues in agricultural TFP measurement. There have been considerable developments in the academic literature over the last 25 years. Powerful methods have been designed, that make it possible to account for some of desirable by-products (public goods, ecosystem services) as well as undesirable by-products (pollution). Several examples of promising work developed in the academic world have been included in the *Insights* and discussed in this paper. They provide useful guidance for the measurement of sustainable productivity growth.

…there are opportunities and limitations in environmentally adjusted TFP indicators…

However, there is still a large gap between academic developments and indicators that are transparent, practicable and therefore useful for policy makers. In particular, there is no simple method to adjust agricultural TFP indices for environmental goods. In theory, TFP indices could be constructed with bad outputs using shadow prices as aggregation weights. However, microeconomic theory shows that the shadow prices that are coherent with input and output aggregation are different from those that reflect the social costs for the society, which tend to be the ones on which environmental economists and policy makers focus.

In addition, recent work has shown that some of the methods developed to account for by-products have raised questions regarding their compatibility with physical relations, such as the coherent material balance between inputs and outputs. The solutions proposed for this have so far proven complex to implement. At this stage, such approaches do not fall into what national statistical agencies can implement on a routine basis.

The incorporation of undesirable by-products in TFP analysis ends up shedding light on the trade-off between "good" and "bad" outputs, measured as pollution intensity or changes in the flow of pollution. The interpretation in terms of sustainability, which often refers more to the level and stock of natural resources rather than the intensity of pollution, is not straightforward.

Given the existing gaps, advances in measuring sustainable productivity growth should not rely only on expanding TFP calculations for non-commodity inputs and outputs. Alternative approaches and methodologies should be explored in parallel, building on available analysis and datasets on the environmental performance of the agricultural sector.

2. How to measure Total Factor Productivity?

Methods for measuring TFP and available indicators

Productivity growth between two periods can be measured as the part of the increase in production unexplained by the growth of inputs. This can be formalised from a production function that represents the technology. The concept of *technical progress* is then captured by the partial derivative of this production function with respect to time. One can also measure technical progress with dual representations of technology, such as cost, profit or revenue functions. In all cases, an estimate must be made, often using econometric methods.

Productivity is measured by dividing an output index by an input quantity index. Economic index theory connects different options for index formulas with the implicit assumptions made for the underlying economic production processes (Box 3). Most frequently used indexes require assumption such as firms operating efficiently. While some indexes do not assume constant returns to scale, accounting rules used in pricing inputs often require this assumption.[8]

One can also distinguish frontier and non-frontier approaches (see Chapter 2 of the *Insights*). The frontier approach makes it possible to decompose changes in TFP into technical progress (shift in a common frontier) and technical efficiency changes (the catching up of a particular production unit). Non-frontier approaches, including standard TFP measures with index numbers, combine both technical change and efficiency changes.

[8] Index numbers can be modelled in such a way that they assume or not constant returns to scale. In the OECD Productivity Database, no assumption on the returns to scale and indexes allow for the existence of increasing returns to scale and mark-ups. See https://www.oecd.org/sdd/productivity-stats/29880111.pdf. Assuming constant returns to scale is less of a problem when applied to national level data, compared to firm or farm level data.

Box 3. Economic Index Theory and Distance Functions

The Laspeyres, Paasche, Fisher and Törnqvist indexes are the most widely implemented indexes following an axiomatic approach consisting of mathematical formulas with some desirable properties. Laspeyres and Paasche indexes aggregate quantities using base versus current period prices, respectively. The Fisher index takes the geometric average of the Laspeyres and Paasche indexes, while the Törnqvist index weights this geometric average by the individual quantity component shares.

The economic theory of index numbers starts from a rigorous representation of the behaviour of the producer. This theory favours the use of Fisher or Törnqvist indexes that are consistent with general representations of technology. They are called "superlative" indexes, since they can be derived from general "flexible" forms. Experts who evaluated the procedure to measure TFP recommended the use of Fisher or Törnqvist indexes (Gardner et al., 1980[18]; Diewert, 2017[19]; Shumway et al., 2017[13]).

The concept of distance function gives a more general framework since it summarises the whole of the technology by a single parameter, which measures the radial expansion of the outputs possible under the technology constraints, for a given set of inputs. Distance functions therefore make it possible to measure the distance of a given company or country from the technological frontier. Malmquist indexes, which are based on distance functions, provide a very general framework. There is, for example, no necessary assumption about returns to scale. In theory, there is no need for price data, although in practice if we want to do without it we have to estimate the distance function, which poses other problems, and are clearly an obstacle for a routine use of this approach by statistical agencies.

The Malmquist index is particularly suited to the inclusion of non-market goods, such as pollution, in productivity indices. If prices are available and producers are assumed to be rational, the Malmquist approach also boils down to the Fisher and Törnqvist indexes, which provides further justification for the empirical use of the latter.

Approaches to measuring TFP

Overall, TFP can be measured through three different approaches: by estimating a production function; by estimating Malmquist indexes which are consistent with some general theoretical conditions; or by constructing simpler but more restrictive indexes.

Estimating a production function requires using an econometric or non-parametric procedure. No restrictive assumption is required regarding market efficiency, producer behaviour and returns to scale, but the estimates are not always robust and subject to a variety of econometric problems (e.g. multicollinearity, outliers, etc.). The estimation of the cost or the profit functions is more robust but requires the assumption that producers are at market equilibrium.

Estimating Malmquist indexes is compatible with very general assumptions. It allows productivity gains to be broken down into technical progress and technical efficiency of a company or a country. This opens the possibility of including “bad outputs” such as pollution. However, it requires either the estimation of a parametric (econometrics) or nonparametric distance function (Box 3). Non-parametric methods, in particular Data Envelopment Analyses, lead to estimates that sometimes lack robustness.

Constructing Fisher or Törnqvist indexes[9] of output, input and TFP growth is relatively simple and give very similar results. However, in order to use prices, costs or factor shares as an approximation of marginal incomes and elasticities, assumptions of efficient producer behaviour and competitive markets are required; assumption of constant returns to scale, while not necessary in theory, can greatly simplify the construction of indexes.

National and international agencies should use a simple index and growth accounting approach

Estimating production functions or Malmquist indexes are often used in academic work, while index numbers are used by national and international agencies. The *Insights* recommends using a growth accounting approach based on Fisher or Törnqvist indexes (OECD, 2022[3]).

The Growth Accounting Approach (GAA) is a popular approach for estimating agricultural TFP growth. It is simple and flexible in modelling multi-output and multi-input production processes.[10] It is also easier to understand and replicate and consistent with the national accounting framework. The GAA makes it easy to calculate the change in TFP from year to year. The GAA is particularly convenient for calculating agricultural TFP across countries because it does not involve the estimation of parameters, while it is compatible with the OECD approach at country level or OECD Productivity Manual (OECD, 2001[8]). Among the limitations of the approach is that growth accounting is an estimator of technical change that does not have a stochastic term. Therefore, the model is not estimated statistically and the usual statistical tests used in econometric work cannot be applied. In addition, decomposition of growth, in practice, requires using prices as aggregators to weigh inputs and outputs. This will be a serious limitation of the approach when one wants to include non-commodity products and non-marketed by-products such as pollutions (Section 3).

Calculating input prices is challenging

One limitation of Fisher or Törnqvist based indexes is that aggregation of quantities relies on the assumption that prices and rental rates to approximate the marginal costs and returns that are supposed to be the proper weights. Questions arise regarding the validity of these assumptions. Variable inputs can be adjusted quickly to their economically optimal level; that is, when their marginal returns are equal to their market price. However, this is not the case for other inputs, such as buildings, land or self-employed/family labour, which are often considered to be “quasi-fixed”. This implies there may be underutilised capacities of capital or family labour. In such situations, shadow prices of these quasi-fixed inputs are the most relevant valuation from a microeconomic level.

The integration of non-commodity outputs and inputs, which are in general not marketed and therefore have no observable prices, raises even more complex issues related to the need for calculating shadow prices (Section 3). It is noteworthy that farm level data, coming from surveys, provide a valuable source of both input quantities and prices. This shows there is research value in combining farm level analysis as undertaken by the OECD’s Farm Level Analysis Network with the work of the OECD on TFP.

[9] Some of the indexes listed in this section are not fully consistent with measurement theory. For example, the Fisher and Törnqvist indexes are not transitive and the chained-Fisher index, which was developed to address transitivity, does not satisfy proportionality. Satisfying these properties is not trivial and each index has relative weaknesses and strengths.

[10] Jorgenson and Griliches (1967[62]) were the first to use the GAA-based index to measure TFP at the national level. More recently, the approach has been used to measure agricultural TFP in the United States (Ball, 1985[59]; Ball et al., 1997[60]) and worldwide (Fuglie and Wang, 2013[61]).

Measurement of outputs

Defining the output aggregate: Gross output or value added

In measuring TFP, an important step is the definition of aggregate output, i.e. the numerator of the productivity ratio. Two approaches can be used, either a measure of gross output or of value added, i.e. gross production minus intermediate consumption (energy, materials and services). The advantage of the concept of added value is that we directly obtain the remuneration of the primary factors of land, labour and capital (Schreyer, 2001[20]). If the objective is to break down the growth in production into several sources, it is nevertheless preferable to measure output as gross production, even if this poses problems of comparison with non-agricultural sectors (Gardner et al., 1980[18]; Shumway et al., 2017[13]).[11]

64. Certain outputs are also inputs to the sector, such as animal feed or self-produced seeds. It would be logical to consider, for example, that corn produced and then consumed by animals is counted both as input and as output. In practice, the data do not always make it possible to identify the self-consumed quantities. For this reason, the OECD Network on Agricultural TFP and the Environment pragmatically recommends using the value of sales and the increase in inventories as a gross output.

Defining output prices, including output support

A second issue is the price system to aggregate the outputs. Microeconomic theory finds that the producer price at the farm level should be used to weight the output quantities after deducting taxes and adding subsidies. However, subsidies should only be added to prices if they are linked to the production decision, and therefore coupled to a product (Chapter 4 of *Insights* (OECD, 2022[3])).[12]

Agricultural support has undergone major changes over time. The general rule is that only payments that increase the return per unit of output should be included in the output prices. The work of the OECD on the classification of support measures within the framework of PSE database (OECD, 2021[21]) makes it possible to know the incidence of each subsidy on the decision-making of the producer.

Accounting for inventories and output quality

The change in inventories is part of the aggregate output. TFP measurements should track, as accurately as possible, changes in inventory to reflect changes in production over time. New outputs and those which cease to be produced, as well as changes in the quality of outputs, pose difficult problems for the measurement of aggregate output. Most experts have therefore recommended constructing "chain" indices. Annual indices are then “chained”, i.e. multiplied with each other over the period to obtain the price variation over the entire period.[13]

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[11] Note that unlike most other agencies, FAO recommends measuring productivity through a value-added approach (FAO, 2018[22]). One reason is that this approach makes it easier to compare the TFP growth between sectors, especially in developing countries, and that data are more readily available.

[12] The System of National Accounts (System of National Accounts, 2008[58]) clarifies that ‘‘basic price is the amount receivable by the producer from the purchaser for a unit of a good or service produced as output, minus any tax payable, and plus any subsidy receivable by the producer as a consequence of its production or sale. It excludes any transport charges invoiced separately by the producer’’. More precisely, Shumway et al. (2017[13]) clarify that ‘net distorting payments (payments based on output in the OECD methodology to measure agricultural support) are added to individual commodity output prices, and distorting taxes (output specific levies) are subtracted. Non-distorting flex payments are treated as transfer payments and not included in output price’. Herath (2020[53]) detail the proposed treatment of various forms of agricultural support in TFP analysis.

[13] The use of chain indexing is to reweight the indexes frequently to reduce “index number bias” that can result when producers make substitutions among outputs and inputs in response to relative price changes.

Changes in the quality of the goods produced pose the same problems. In order to isolate what is really the "productivity" component in the evolution of production, it is necessary to make sure to compare goods of similar quality in each period. In sectors where there is a rapid change in quality, this may require methods such as hedonic prices to control for these differences in quality between two periods.

Measurement of inputs

The measurement of inputs in TFP analysis raises particular problems. The denominator of a TFP index should reflect the productive “service flow” of the inputs used. Estimates of the service flows of inputs such as buildings, equipment, machinery or land are much less straightforward than the service flow of intermediate inputs.

Intermediate inputs

Conventions adopted by United Nations agencies define intermediate inputs as goods and services consumed in the production process (see Chapter 8 of OECD (2022[3]).

The main problem in measuring these inputs is taking into account new inputs over time, variations in the composition of the aggregates and in the quality. Changes in the characteristics of an individual input and the composition of the basket, e.g. fertilisers or phytosanitary products, can lead to a poor estimation of price variations and therefore of productive service flows (FAO, 2018[22]). Despite these challenges, an appropriate measurement of quality changes of intermediate inputs helps more precise measures of TFP.

New products, and changes in the quality of existing inputs, can be addressed simultaneously by constructing a price index that captures these changes (Chapter 12 in *Insights* (OECD, 2022[3])). Several methods have been proposed, such as hedonic regression techniques to control for changes in quality and composition. In this area, the pioneering work of the USDA ERS to adjust the quality and composition of fertilisers, for example, is now a source of inspiration for several government agencies of OECD countries.

Measuring labour input

Labour force statistics and labour productivity measures published by different organisations often differ in terms of the concept, definition and coverage of the agricultural sector. This makes it difficult to compare productivity performance across countries. The data sources are also different, since some come from household surveys, others from administrative sources. International initiatives, such as FAO's Global Strategy to improve Agricultural and Rural Statistics have provided guidelines for national statisticians. The *Insights* (OECD, 2022[3]) and the UN System of National Accounts also provide a coherent framework.

The flow of labour services is the relevant input quantity in TFP analysis in the agricultural sector. This flow of services encompasses the knowledge, skills and competencies of workers that contribute to productivity and economic growth. These can be acquired through education, training, experience, and improvement in health.

Measuring the quantity of productive labour raises data issues, such as for part-time farms on which the actual number of hours devoted to farming is often poorly measured. Labour on some farms is mainly based on contract work by outside companies, which in this case must be considered as intermediate consumption, under services. The measurement of labour service flows should rely on the number of hours of different categories of workers invested in the production process, distinguishing between family, salaried and seasonal work and taking into account work peaks and periods of underutilisation of the workforce present in the holding. Such data are only available in a limited number of OECD countries. As shown by Cahill and Rich (2021[23]), the results are particularly sensitive to the different conventions adopted, which are themselves dependent on the available data.

The "price" component of labour input can be obtained from all remuneration, in cash or in kind, for workers' services. However, this must be calculated for self-employed workers and other unpaid workers. The method proposed by Jorgenson et al. (1987[24]) to control variations in the composition and quality of labour input supposes a fine distinction by level of qualification, age and gender to find correspondences with the remuneration of equivalent characteristics in third sectors. A very detailed decomposition of US agricultural labour was carried by the USDA Economic Research Service,[14] but it is difficult to use in a harmonised manner in the different OECD countries. Chapter 8 of the *Insights* (OECD, 2022[3]) provides recommendations, including the possibility of allocating residual remuneration to labour starting from an accounting identity.

Capital input

The concept of capital can be very broad, since it can include land, intermediate consumptions and even human capital. Here, we consider the buildings and equipment that are used in the production process, without being consumed in the production year.

The challenges of measuring non-land capital have been very extensively studied in the literature. Chapter 9 of the *Insights* (OECD, 2022[3]) and Shuwmay et al. (2017[13]) provide guidelines. The flow of capital services is the theoretically correct component to include in productivity indices, but it can rarely be measured directly. The most widely used convention is to assume that services are proportional to a stock of capital. This allows a perpetual inventory method to be used where the investments accumulate over time, from which the outflows (scrapings) and the reduction in productive services by a unit of capital over time are deducted.

Constructing the stock of capital in this manner requires long-term investment data that span far beyond the period for which TFP is analysed. Ball et al. (1993[14]) have proposed a framework that makes it possible to adjust the patterns of physical and economic depreciation according to the types of equipment and buildings. [15] Ball et al. (2020[25]) have used this approach to derive capital services from capital stocks for 18 OECD countries. However, the choice of the parameters used to represent the physical depreciation curve, the average lifespan of equipment and their distribution remains a challenge. Collaborative work is needed for more coherent data across countries.

The weighting of the service flows of the different types of capital, and the weighting of these services in the aggregate of inputs, requires using prices. The OECD (2001[7]) considers that the costs of using inputs should represent the amount of rent that one would charge for it (opportunity cost) and recommends distinguishing each type of asset. The user cost can be made up as i) the cost of financing the asset, i.e. the cost of depreciation, plus the cost of interest applied to the value of the added asset, and ii) net capital gains or losses or revaluation of the asset (OECD, 2001[8])). Consistent with this idea, different methods are used by government agencies to construct user costs of capital, based on interest rates, either anticipated or observed. For example, the USDA-ERS method is based on calculating annuity prices from an expected real interest rate (Shumway et al., 2017[13]). The debate over whether to deflate the interest rate in calculating the user costs of capital when other prices are not (e.g. labour) remains under discussion.

[14] See https://www.ers.usda.gov/publications/pub-details?pubid=103266. See Ball et al. (2016[56]) for the methodology.

[15] For constructing capital services, rather than a linear depreciation, Chapter 9 of the *Insights* recommends to use the general pattern of decay that relies on the family of hyperbolic efficiency functions is given by $S_t=(L-t)/(L-\beta t)$ for $t \leq L$, where S_t is the relative efficiency of an asset of t years of age, L the service life and β describes the form of the depreciation. Regarding the value of the parameter β, we recommend also to conduct a survey or a panel of experts, so as to use the same parameter across OECD countries or motivate differences.

Several components of capital can be considered as "quasi-fixed" inputs, that is, their level does not immediately adjust to prices. Hence, they can be partially under or over used in the short run. The methods for correcting these capacity utilisation rates are not robust, if only because there are occasional peaks in usage, and there are not always spare equipment or buildings available for rent. One can take this short-term rigidity into account by valuing the quasi-fixed factors with a shadow price.[16] Empirical approximations are possible that avoid the use of econometric estimates, especially if constant returns to scale is assumed.

Land input

Land is considered as a “non-depreciating asset” in systems of national accounts, such as that of the United Nations. As for other inputs, the contribution of land to TFP requires measuring a flow of services. The measurement of the stock of land is based on the number of hectares put into production and is generally fairly accessible. However, land can be cultivated with very little intensity (savannahs, mountain pastures) or partially forested. The hypothesis of a proportionality between the flow of services and the stock measured in hectares is only valid if we distinguish the types of land. For example, the services drawn from a hectare of arable land and pastures are different. To measure the flow of productive services, the land input would need to be broken down by soil type, climate, fertility, and other characteristics that affect its productive capacity.[17] Failure to account for all of these differences in quality can lead to biased TFP estimates and mistakenly attribute effects to technical progress (FAO, 2018[22]).

It is possible to use the market price of land or the unit value of rentals to control for a particular type of land in a particular area, to control for differences in quality (Ball et al. (2010[26]). Such values can be extrapolated to owned land, but the market must be transparent and free from transactions for uses other than agriculture. The FAO (2018[22]) proposes using the median unit value of rents for land owned in the same region, or failing that, to impute this with a statistical model, with a fine decomposition of land and land use. Another possibility is the construction of a valued stock to which an interest rate, taxes and land improvements are applied, as for capital. However, like some other forms of capital, land can be viewed as a quasi-fixed factor, and the use of land input by a producer is not necessarily at its optimal level in the short run, suggesting the use of shadow prices might be more appropriate.

Aggregation, input weights and accounting identity

The way in which the inputs are aggregated, and the different input weighting schemes that enter the denominator of the TPF indices are the subject of different conventions between the agencies working on this subject. This often makes the measurements difficult to compare. This poses a problem in comparisons between countries, since particular weighting schemes can give more or less weight to a factor which tends to decrease over time (e.g. labour) compared to another which tends to increase (e.g. capital).

[16] Such a shadow price can be deduced quite simply from duality relations if we have an econometric estimate of a representation of the technology. Intuitively, it is the price that corresponds to the situation where the optimal adjustment of the input (which cannot adjust freely in the short run) would match the observed level.

[17] The effort by the USDA ERS in this area is worth mentioning. In order to construct a stock of land implicitly as the ratio of the value land in agriculture to the corresponding price index each country, the authors compiled data on land area and average value per hectare for no less than 3 582 states or regions across the seventeen countries. They estimated spatial price indexes (i.e. purchasing power parities) for land accounting for heterogeneous soil types and associated soil characteristics (Ball et al., 2016[56])

If an average wage rate in the non-agricultural sectors is used to calculate a cost of using family labour of equivalent type; if a land rental price is used to value self-owned land; and an interest rate (e.g. government bond rate) is applied to the entire stock of equipment and machinery, plantations and infrastructure, in total the calculated cost of aggregate inputs will probably exceed the gross revenue of the sector agriculture in most OECD countries, even after subsidies are included in revenues. A large and systematic gap between gross output and the cost of all inputs would be questionable. Deficits are of course possible and they can last for several years. However, over a longer period, the quasi-fixed inputs are supposed to adjust to their level of remuneration. It is conceivable that family farms, which are the dominant model in most OECD countries, may accept lower primary factor pay rates than pay in other sectors.

One of the most respected theorists on this subject, Diewert, defended the idea of calibrating the rental rate of different forms of capital so that the gross receipts are equal to total costs, i.e. the so-called "accounting identity". This solution is consistent with microeconomic theory, which says that profit is exhausted in factor remuneration if markets are competitive, and returns to scale are constant. Since variable inputs (intermediate consumption or materials) can be adjusted to their optimal use in the short run, it is justified to associate a market price to represent their marginal productivity and starting from the accounting identity to adjust the residual income as a return to quasi-fixed factors.

If the quasi-fixed factors are not at their optimal long-term level, their marginal remuneration gives shadow prices. These can be estimated econometrically, but the assumption of accounting identity makes it possible to approximate them using the residual remuneration. Some authors consider that the residual remuneration should be allocated to land (Shumway et al., 2017[13]). However, the self-employment and risk-taking of the manager could also be the residual remunerated factor. In Chapter 9 of the *Insights* (OECD, 2022[3]), it is suggested to price the various primary factors (land owned, independent and family work, buildings) at their market value to build user costs, then distribute the accounting identity residual proportionally to the usage costs among the quasi-fixed factors. Due to the increasing use of third-party equipment, equipment could be treated as intermediate consumption, i.e. as variable inputs, even though one may consider a more detailed distinction between owner operated and custom services.

3. How can TFP measurement be expanded to include environmental outcomes?

Natural capital, public goods and externalities

Non commodity outputs and inputs as "market failures"

Several non-market goods are involved in the agricultural production process. Some inputs or outputs exhibit externality or public good characteristics. Integrating these non-marketed inputs and outputs into TFP measures is extremely challenging.

Agricultural activity generates non-commodity goods, which sometimes constitute outputs with high social value, even though they are not subject of remuneration, an issue well identified as "market failures". Some of these outputs are public goods, in the sense that they provide benefit to several users at the same time.[18] They can take the form of a variety of ecosystem services (Box 4). In some regions, the environmental services and the public goods provided by agriculture may have an economic value greater than agricultural production *per se*, for instance in protection against flooding with wet meadows playing the role of buffer or in resilience to fires by grazing in the undergrowth. Ignoring the value of these services within the scope of agricultural outputs poses a problem. Not counting non-market goods produced and

[18] Formally public goods are simultaneously non-rival and non-excludable.

consumed in the production process can introduce a bias, unless this good is available for free to the producer and society as a whole and is not subject to scarcity.

Conversely, agricultural production activity uses as inputs goods that do not carry a market price, such as clean air, clean water, or services provided by ecosystems. When agricultural production consumes or destroys a form of natural capital, it is not defensible nor consistent with the objectives of preserving natural resources to ignore the use of such an input for the sole reason that it is not correctly reflected by the market. There are many examples of such degradation of natural capital. Soil degradation by modern agriculture is a global problem, and IPBES (2018[27]) shows that this threatens the future agricultural production potential of the planet. A part of grain production in North America and vegetable production around the Mediterranean is based on the exploitation of fossil aquifers. Water resources are becoming scarce in some countries, and its quality is deteriorating (sediment loads from soil erosion, salinisation, use of chemicals).

Agricultural production also results in undesirable by-products. This is particularly the case for air pollution from methane and nitrous oxide emissions, and ammonia, which have negative impacts on the environment and human health. The same is true of geochemical flows, nitrogen and phosphorus, of particular concern, since the current levels of run-off and leakages are already considered worrisome.[19] Disposing of undesirable by-products may require resources that cannot be used for the production of desirable outputs and will, therefore, affect productivity. Therefore, there are potential trade-offs between agricultural production and reducing undesirable by-products. For instance, including trade-offs between production and biodiversity losses in TFP indicators is a challenge. First due to the difficulty of measuring biodiversity; second, because the complexity of the technological linkages between the two.

Box 4. Non commodity outputs of agriculture

The United Nations (UN) Millennium Ecosystem Services Assessment (MA) defines ecosystem services as the benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as regulation of floods, drought, land degradation, and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other nonmaterial benefits. Agriculture and ecosystem services are closely intertwined, giving rise to the term “agro-ecosystem” to denote the complex relationships between agricultural production and surrounding ecosystems. While agriculture often benefits from provisioning and regulating services, production can also affect the quality and quantity of these services, in both sustaining and degrading ways

The EU Commission set up a thematic working group to define the “public goods” produced by agriculture that might not be rewarded at their fair level by markets.[1] The group came up with the following list: agricultural landscapes, farmland biodiversity, water quality, water availability, soil functionality, climate stability (carbon storage), climate stability (GHG emissions), air quality, resilience to flooding and fire, and rural vitality. Farmers supplying these goods could potentially be granted payment for public goods, in particular under the EU Common Agricultural Policy “rural development” programme.

1. https://op.europa.eu/en/publication-detail/-/publication/ca4c2459-1533-4642-bf02-ebaacbb9b37c/language-en/format-PDF/source-search.

[19] Beyond the “planet boundary” in this area, according to the planetary boundaries concept that presents a set of nine planetary boundaries within which humanity can continue to develop and thrive for generations to come. See https://stockholmresilience.org/research/planetary-boundaries.html.

Negative externalities come back to agriculture

The nexus between environmental issues and TFP is a two-way street. Indeed, the "bad outputs" of pollution or other forms of negative externalities will also influence agricultural productivity. For instance, soil degradation due to erosion or inefficient use of inputs, can considerably affect plant growth. In terms of GHG emissions, each degree of daily temperature above 30°C greatly reduces the yields of plants such as corn, soybeans and wheat (Schenkler and Roberts, 2009[28]). The TFP of the agricultural sector will therefore be negatively impacted by emissions, and when agriculture contributes to this pollution (as for nitrous oxide or other emissions), today's "bad outputs" become also tomorrow's "bad inputs".

Accounting for non-commodity inputs and outputs in TFP measurement

Attempts to include environmental issues in TFP measurement started in the mid-1990s. Some 25 years of academic work now make it possible to shed light on the different interactions between the measurement of TFP and environmental goods.

Microeconomic foundations of TFP measurement in the presence of non-commodity inputs and outputs

Traditional TFP measures have failed to account for non-commodity inputs and outputs. One reason is the difficulty of measuring service flows and quantities emitted (cases of non-point source pollutions). Another is that synthetic TFP indices, at least in the GAA approach, require weighting both inputs and outputs with prices, or price approximations. Since desirable by-products, such as public goods (e.g. open landscapes valued by tourists) and undesirable by-products (e.g. leakage of pesticides, nitrogen) are seldom marketed, no market price is available. In addition, when a price is available, for example, through markets for emission permits, or estimates of society's willingness to pay to avoid pollution, it does not necessarily provide an appropriate way to value these by-products.

Diewert provided strong theoretical foundations for TFP analyses in the 1980s, grounded in microeconomic theory and the "economic theory of index numbers" (Box 3), which have proved to be a very useful guideline. When facing the new challenge of integrating non-commodity inputs and outputs into TFP measurement, microeconomic theory offers clear guidance. Chapter 3 of the *Insights* (OECD, 2022[3]) provides a comprehensive description of the challenges raised by TFP measurement with desirable and non-desirable "by-products" based on microeconomic theory.

Unless corrected for the existence of by-products, TFP growth measures cannot separate technical change from growth in the supply of the by-product. Robert Chambers in Chapter 3 of the *Insights* shows the magnitude of the measurement error in such cases. Measuring environmentally adjusted TFP growth would require adding a term to the traditional TFP growth index that would correct for the changes in the bundle of by-products, weighted by their cost elasticity. The additional term would be negative if the additional by-products of agriculture production are "bads" rather than goods.

Producer costs, social benefits and regulations

From the point of view of the producer, the standard TFP measure is accurate in the sense that, the producer faces no cost or production constraint if pollution is costless and unregulated. However, from the social point of view, the measure fails to account for the changes in the production of non-marketed public goods and for the changes in the production of "bad outputs". This situation is rather similar to the well-known shortcomings of the Gross Domestic Product as an indicator of welfare.

One consequence of ignoring undesirable by-products, for example, is that environmental regulations will necessarily be considered as detrimental to TFP growth with traditional TFP measures. Indeed, regulations require resources to be diverted from traditional productive activities to pollution abatement, and standard TFP measures ignore the fact that regulations may lead to a reduction in environmentally detrimental outputs (Kumar, 2005). Firms in industries that face environmental regulations would typically find that their productivity is adversely affected since the costs of abatement would typically be included on the input side, but no account would be made of the reduction in effluents on the output side. However, the regulation could have a positive impact on sustainable productivity growth if it creates the right incentives for an efficient reduction of negative environmental externalities.

Jointness, disposability and abatement costs

The reference to microeconomic analysis shows that two aspects are important in the presence of undesirable by-products. First, the representation of the technology must account for cases where there is a joint production of desirable output and undesirable by-products. This corresponds to the case where production of "good" outputs is necessarily accompanied by the joint production of a polluting substance (e.g. methane emissions). Second, the undesirable by-product cannot be freely disposed of. In other words, the reduction of the "bad output" will be costly; resources will need to be diverted – from agriculture or other sectors – to clean, or offset, pollution, or production must be cut back, or fines must be paid.[20]

Because information on the costs of abatement of undesirable by-products is often found to be unreliable or unavailable, authors have focused on modelling production technology explicitly. This involves measuring the cost of the undesirable by-product as a reduction in the production of a "good" output, or as an increase in inputs. This leads to defining abatement costs as the reduced "good" output production that occurs when inputs are reallocated to pollution abatement activities (Chung, Färe and Grosskopf, 1997[29]; Färe, Grosskopf and Pasurka, 2007[30]). For that purpose, concepts such as distance functions, which can be used to construct Malmquist indexes, have proven to be useful, particularly because they do not require collecting prices of damage costs of non-commodity inputs and outputs to be collected (Box 3).

Representing pollution as an input or as an output

Undesirable by-products can be either treated as an input or an output (in some cases the output is pollution abatement). A first approach is to consider undesirable by-products as inputs. This allows the undesirable by-product (e.g. pollution) and the desirable output to be treated as complements rather than substitutes: reducing pollution must be accompanied by either decreasing desirable outputs (hence the idea of considering pollution as an input), or reducing other productive inputs so that resources can be used for pollution abatement activities. This approach has been successfully used by Hoang and Coelli (2011[31]) to construct measures of TFP in agriculture adjusted for changes in the nutrient balance, caused, for example, by using synthetic fertiliser.

Another approach is to consider harmful by-products as outputs, and considering that there is a technical relation between the level of desirable output and the undesirable by-product. From a microeconomic standpoint, this involves assuming that undesirable by-products are "weakly disposable outputs"; and that one cannot produce good outputs without bads (null jointness assumption (Färe et al., 1993[32]) and the disposal of undesirable by-products has some cost. A considerable body of literature, largely surveyed by Murty and Russel (2002[33]) and Dapko, Jeanneaux and Latruffe (2016[34]), relies on these two approaches.

[20] Weak disposability refers to a situation where, if all inputs increase proportionally, outputs might decrease due to congestion. In TFP measurement, the concept has been extended to characterise technology that includes undesirable outputs. In such cases, weak disposability requires that reducing undesirable outputs requires decreasing desirable outputs or increasing inputs by the same factor.

In order to be able to credit firms for the reduction in "bad" outputs, the standard approach relying on distance functions was generalised to allow for non-proportional reductions in undesirable by-products and good outputs.[21] This procedure has been successfully used in numerous studies in agriculture. For example, Ball et al. (2001[35]) identify large discrepancies between the standard TFP measure and the measure that accounts for undesirable by-products such as pesticide run-offs. Fare et al. (2012[36]) show that measures of TFP not crediting GHG emissions reductions generate poorer productivity changes when resources from production of good outputs have been diverted to reduction of emissions.

These approaches, while theoretically consistent, raise numerous empirical problems (Section 2). In addition, they require using either econometric or non-parametric (Data Envelopment Analysis) methods which are ill suited for standard use by national agencies or international organisations. Furthermore, these methods rely on empirical estimations of marginal abatement costs for the producers. The transfer of these methods from the academic world to statistical agencies and policymaking remains a challenge.

Shadow prices and shadow costs

Using a Fisher or Törnqvist index when TFP is corrected for the existence of by-products is theoretically possible. Gu, Hussain and Willox (2019[9]) showed that the growth of TFP will be the difference between the growth of an aggregate of "good" output and the growth in undesirable by-products and the growth of an aggregate of capital, labour, land and intermediate consumption. Chambers et al. (2014[37]) have developed the formula that adjusts a traditional Törnqvist TFP index for the existence of an undesirable by-product. However, there are practical obstacles to constructing this index.

When goods and services are not marketed, shadow prices can be defined and used instead of market prices. The first possibility is to use external estimates of shadow prices. For instance, a market approximation such as *emissions trading prices* for those pollutions that are subject to a market-based regulation. Measures of *willingness to pay* or willingness to accept could also be used applying methods such as contingent valuation, social experiments or discrete choice modelling. Among the pioneering works, Pittman (1983[38]) managed to account for polluting activities in TFP indices using *external estimates for shadow prices*. Brannlund, Färe and Grosskopf (1995[39]) analysed the impact of environmental regulations on firms' profits calculating a ratio between profits with and without environmental restrictions as an approximation of "shadow prices" that could be used for integrating undesirable outputs in TFP analysis.

However, the shadow prices that should be used in the construction of TFP indices are not necessarily those that reflect the damage for the society as a whole. The most consistent theoretical approach would be using the actual cost for the producer of avoiding non-desirable outputs. That is, the shadow prices of by-products should reflect the private cost that agricultural producers would face to reduce pollution by one unit if this translates into a reduction in their profit. These shadow prices are therefore conceptually different from the social costs of externalities. The latter include all the costs to society of the impacts of pollution on health, water or air.[22]

The shadow prices that are theoretically consistent with TFP analysis can be derived from the producers' optimisation programme, assuming that opportunity costs of abatement activities can be modelled as the

[21] Chung, Färe and Grosskopf (1997[29]) used a using a "directional" distance function. The standard distance function defines the whole production technology as the maximum factor in which goods and bads can be expanded proportionnaly while production remains possible. The directional distance function defines the whole production technology as the maximum feasible expansion in good outputs and contraction in bad ouputs. The standard Malmquist index was altered and renamed "Malmquist-Luenberger" TFP index.

[22] Leleu (2013[48]) explores the linkages between the concept of shadow prices for the producer and the society's social values.

foregone production of “good” output (Färe, Grosskopf and Pasurka, 2007[30]).[23] Fare et al. (1993[32]) have estimated shadow prices from distance functions.[24]

However, empirical difficulties remain to be resolved. Chapter 3 of the *Insights* (OECD, 2022[3]) shows that it “seems inevitable that TFP measures need to accommodate unpriced by-products by measuring their shadow prices”. It also points out important obstacles for adjusting Fisher and Törnqvist TFP indexes for the existence of non-commodity inputs and outputs.

Examples of empirical measurement of environmentally adjusted TFP

Adjusting TFP for air pollution

Several attempts have been made for adjusting agricultural TFP growth for air pollution, and in particular for the emission of GHG, that can be more easily monitored than other emissions like ammonia.

Empirical results were obtained by Färe et al. (2004[40]) for firms in the industrial sector in the context of air pollution. Their approach accounts for the fact that a firm (or plant or industry or country) has succeeded in producing desirable output while simultaneously accounting for reductions in the undesirable by-product that pollutes the air. The implicit benchmark is the highest ratio of good to bad outputs, i.e. this can be thought of as a type of environmental productivity index.[25] Some OECD countries have started to implement a precise accounting system of GHG emission at the farm level (Ireland is particularly ahead in this area), which shows that developments for agriculture are promising.

In Chapter 4 of the *Insights*, Ang, Dakpo and Pieralli have developed a GHG emission-adjusted TFP for agriculture using the USDA-ERS international agricultural productivity data (Fuglie and Rada, 2015[12]), that they combine with data on emissions from livestock, synthetic fertilisers, and land use changes from FAOSTAT. They find significant differences between conventional TFP and GHG-adjusted TFP, even though interpretation of the results is sometimes difficult, in particular those related to land use change emissions. Whether these problems refer to the difficulty of estimating such emissions or to the sensitivity of the estimation method to outliers needs to be explored further. There is still a major gap between these estimations and the more transparent and intuitive indicators that are expected from national statistical agencies.

Adjusting TFP for pesticide and fertilisers leaching and run offs

Agriculture is a source of biogeochemical pollution that affects water (nitrates, phosphorus) and air (ammonia, nitrous oxide, methane, see Zhang, (2022[41]). Another source of air and water pollution is pesticides. The damages and social costs on biodiversity, as well as human health, maybe considerable, even though it is difficult to find precise estimates (Tang and Maggi, 2021[42]).

[23] Chambers (2016[47]) shows that distance functions can be used to decompose the growth of production into a variation of good and bad outputs and inputs, and to impute the fictitious price of “bad inputs”. These shadow prices for “bad outputs” can be derived from the elasticities of “good” outputs and inputs combined.

[24] They exploit the duality between the directional output distance function and the revenue functions and used it to value by-products such as the runoff and leaching of pesticides into surface and groundwater. It is then possible to obtain the (optimal) private cost of reducing the production of unwanted outputs for the producer.

[25] They find, for example, that for the industrial sector and based on a restricted number of air pollutants the United States would produce 1.39 times the level of good outputs if it used the same level of inputs and produced the same level of pollutants as the (hypothetical) reference country. But that at the same time, it would produce 1.27 times as many bad outputs. The ratio of the two corresponding indexes yields an environmental preformance index of 1.1.

Several studies have attempted to adjust agricultural TFP measures for the negative environmental impacts of agrochemicals. A framework methodology was defined by Färe et al. (1993[32]), who identify pollution costs of pesticides by US state and by year. Their method makes it possible to estimate shadow costs that could be used to internalise the external costs associated with agricultural production. Firms are credited for reductions in undesirable outputs, as well as for increases in good outputs. They account for an increase in TFP when, other things equal, a state has managed to maintain its production without using more input while reducing pesticides or fertilisers leaching and runoff. A reduction in TFP is measured for a state that has increased its unadjusted TFP but has increased its leaching and runoffs.

Ball et al. (2001[35]) have used this framework in an ambitious effort to adjust productivity growth for pesticide and nitrogen leaching and runoff. They find that, for many US states, the TFP growth adjusted for water contamination caused by the use of agricultural chemicals is higher than the non-adjusted growth because of improvements in pesticide spreading and nitrogen use. Note, however, that total pesticide use may have increased. This result illustrates that TFP focuses on intensity, rather than the absolute level which is associated more with sustainability. Hoang and Coelli (2011[31]) have gone further in including in their TFP a complete nutrient balance, so as to ensure that the results are consistent with physical reality. They measure an efficiency in nutrient use that they decompose into different sources of changes in environmental efficiency.

Environmentally-adjusted TFP measures reward output growth and penalise pollution growth for a given level of input use. They can provide a more complete image of the global performance of farms than standard TFP indices. In addition to adjusting TFP for changes in the emission of undesirable by-products, one major benefit of such approaches is to estimate shadow costs of nutrient reduction, which could provide a useful indicator of the cost of control for emissions at the farm level.

Data on nitrate leaching has improved considerably recently (Zhang, 2022[41]; Tsagris and Tzouvelakas, 2019[43]), as has the data on pesticide use and leaching (Tang and Maggi, 2021[42]). There are global initiatives to tackle the nitrogen problem (Kanter et al., 2020[44]). This could provide considerable impetus to develop the measures of adjusted TFP on chemical leaching and runoffs.

TFP and water

Water is crucial for food security as well as environmental sustainability and equity on a worldwide scale. Because agriculture competes with alternative uses in several areas where aquifers are becoming increasingly depleted, adoption of innovative techniques that save water without reducing output should be reflected in TFP measures even when water is not priced and counted as an input. Water quality is also an issue due to nitrate, phosphorus, animal waste and pesticide pollution as well as salinisation. Pharmaceutical and veterinary drugs have also become a significant problem, which is expected to get worse in the future.

There have been attempts to decompose TFP measurement into changes in shadow value of water, and water quantity and quality over time (Vrachioli and Stefanou, 2020[45]). More specifically, Vrachioli and Tzouvelekas, in Chapter 10 of the *Insights*, have decomposed TFP changes to identify an “agricultural water effectiveness” component as well as a climate effect. The changes in irrigation efficiency appear significant in some EU countries, even though, the robustness of the results is uncertain, due to data limitations.

An assessment of the strengths and weaknesses on TFP methodology and alternative methods

The problems remaining: Material imbalances and uncertain signs of shadow prices

Recent literature has identified conceptual problems with the introduction of non-commodity outputs and inputs in TFP analysis (Dakpo, Jeanneaux and Latruffe, 2016[34]) (Chapter 3 of the *Insights*). Treating undesirable by-products as an input or as a "bad" output both raise questions, since there is no guarantee that these approaches are consistent with reasonable physical relations between inputs, outputs and undesirable by-products. This has been known as the "material balance constraint" problem. Treating the undesirable by-product as an output under the assumption of weak disposability is not fully consistent with the conservation of material, i.e. the first law of thermodynamics (Hoang and Coelli, 2011[31]).[26] Treating the undesirable by-product as input raises rather similar problems (Murty and Russell, 2002[33]; Atkinson and Dorfman, 2002[46]).[27]

Chapter 3 of the *Insights* explores these aspects in a rigorous way and illustrates how the various assumptions necessary to adjust TFP measures could involve physical inconsistencies. For instance, they could mean that doubling the number of hens and the quantity of feed would double the production of eggs but leave the manure constant, which is a form of violation of material balance, since it would require that each hen generates half as much manure as before. Attention should be paid to ensure that the representation of the technology respects elementary biological processes.

Chambers (2016[47]) also shows that it is possible to define a shadow price for the by-product, which can be approximated by dividing the observed profit by the quantity of by product. Output growth decomposition can then be corrected by the change in the by-product weighted by the negative of its marginal economic rent. This nevertheless does not solve all problems. The calculation of the rent of the by-product is difficult if one accounts for quasi-fixed factors, for which it is necessary to calculate a shadow price (quasi rent). Furthermore, it may also lead to inappropriate signs for the shadow prices (Leleu, 2013[48]).

Potential solutions

The assumptions necessary to account for by-products in TFP analyses are not always consistent with physical laws that govern the joint emissions of good and bad outputs, such as material balance, nor with the sign of the shadow costs for society. This is not good news for practitioners. A proper distinction of the impact of by-products from "pure" technical change would require a rather complex representation, in which the interaction of the undesirable by-product and the output is explicitly modelled as an intermediate input (Murty, Russell and Levkoff, 2012[49]).

Recent developments have attempted to solve such problems.[28] Chapter 3 of the *Insights* suggests representing the firm's production technology using multiple sub-technologies, one generating the intended

[26] Leleu (2013[48]) suggests to treat at least some of the undesirable by-products as strongly disposable and to relax the assumption of null-jointness between good and bad outputs. In practice, this could correspond to cases where an investment in some equipmeent offset some pollution, breaking the proportionality between the good and the bad.

[27] The use of directional distance functions does not solve all problems and it is not sure that they are consistent with the physical flows that are coherent with production modelling.

[28] Forsund (2009[54])(2009) and Murty et al (2012[49]) (2012) proposed an approach so that for a given level of inputs there is a minimal level of pollution, and the presence of inefficiency yield additional pollution to this minimal amount (Dakpo, Jeanneaux and Latruffe, 2016[34]). Leleu (2013[48]) developed an approach that ensure the right sign for the shadow values of the undesirable by-products. Hampf and Rodset (2014[57]) combined mass-energy identity equations and a particular form of disposability in directional distance functions. Yang and Pollitt (2009[55])(2010), Hoang and Coelli (2011[31]) propose to model explicitly the Material Balance Principle that regulates the way materials in inputs are transformed into desirable outputs and polluting emissions. See Dakpo et al (2016[34]) for a survey of promising methods.

outputs and a second one generating the unintended outputs. Promising solutions rely on an explicit representation of the material correspondences between the various traditional inputs (e.g. feed, seeds, fertilisers, animals, manure, soil and water), outputs and by-products. Dakpo et al. (2016[34]) conclude their review by claiming that methods based on the estimation of multiple frontier technologies are more promising due to their strong theoretical background, and they will probably become the core of future research in eco-efficiency evaluation.

It is noteworthy that all these solutions introduce extra complexity in an approach that was already too technical and cumbersome to be adopted as a routinely published indicator by statistical agencies. In spite of progress in data and many theoretical advances in how TFP should be adjusted for undesirable by-products, the gap between academic research and operational indicators has remained wide.

4. A way forward

Productivity is a key indicator of the performance of the agricultural sector. TFP is a well-established way to measure productivity with great potential to further illuminate the policy debate. The discussions on productivity need to incorporate the environmental impacts of agriculture to provide a more accurate reflection of the performance of the sector. There are several efforts underway to measure the environmental performance of agriculture, including the OECD Agri-Environmental Indicators. These efforts can be used in a complementary manner to traditional TFP calculations for a more comprehensive discussion of the sectoral performance. The *Insights* (OECD, 2022[3]) also identifies the current state of the art thinking and emerging best practices in terms of methods to adjust TFP measurement to account for some environmental impacts.

Different approaches and conventions have been analysed in the literature and by the OECD Network on Agricultural TFP and the Environment. This work has identified available options for constructing TFP indices and their potential for country benchmarking and policy impact analysis, assessing the maturity of the methods to expand TFP measurement to include environmental outcomes, and providing some guidance for the way forward. The OECD can enhance its role to facilitate exchange of knowledge and experiences among different types of experts and to promote comparative policy analysis applying alternative approaches across countries.

Guiding data collection efforts

For international comparisons of TFP, a major data effort has been carried out by international and national agencies. The heterogeneous quality of primary data limits the analysis to simple indicators, which do not meet all the recommendations of expert panels (e.g. Shumway et al. (2017[13]). On the other hand, some OECD countries have developed sophisticated methods for measuring TFP and identifying the source of growth through GAA.

The Economic Research Service of the USDA has developed the International Agricultural Productivity database that, while built on more aggregated FAO data, provides international comparisons for agricultural TFP that are currently used by OECD and other agencies. The OECD and its TFP Network can help host and expand a common dataset of traditional TFP measures using simplified procedures that build on existing initiatives.

Best practices should be progressively adopted. The OECD could build on existing efforts to promote best practices and, possibly, hosting harmonised data. Coordination and the development of similar conventions and data are particularly needed to measure capital (depreciation patterns, service lives, etc.);

in the pricing of land, in adjusting for quality and new products, including intermediate inputs (chemicals), and the aggregation of different outputs. The OECD and its TFP Network could work with national agencies to converge towards best practices and standards on measuring agricultural total factor productivity, some of which have been identified in the *Insights*.

Promoting the use of TFP analysis for policy advice

Despite its limitations, traditional TFP numbers are an important tool for policy analysis and OECD should contribute to improve their use and interpretation. The OECD is in a good position to promote TFP analysis that enlightens policy debates on productivity and beyond. Further work and research on the different sources and patterns of productivity growth can lead to useful policy implications. There is also scope for more in-depth analysis of the causes and effects of productivity developments. For instance, investigating the role of investment on Research and Development and other drivers and determinants of TFP gains and their different paths; or analysing the effects of productivity growth along the supply chain and the shares of productivity retained by the different stages in the chain.

The OECD has a comparative advantage in analysing sustainable productivity growth in agriculture and its policy implications. Its work on economy wide productivity measurement, together with its work on environmental issues, provide a good basis for identifying methods and indicators to better define and analyse sustainable agricultural productivity growth. The links with the working parties of the Committee for Agriculture can ensure a discussion on performance that is both evidence-based and policy relevant.

Diversifying the approaches for the measurement of sustainable productivity growth

The limitations of the traditional TFP indicators have increasingly become apparent in the context of the Sustainable Development Goals. It is now asked from the agricultural sector to produce more food without depleting land and water resources, to reduce its negative environmental impacts, and to contribute to climate mitigation, including through carbon sequestration. Advances in the measurement of sustainable productivity growth will require investing in different methods and approaches for TFP indicators to reflect such performance. The OECD has a role in promoting alternative options and avenues to assess the productivity and sustainability performance of agriculture and facilitate the comparison of results and its interpretation for policy purposes.

The OECD contributes to harness insights from the buoyant academic research in this area. Despite their complexity, the recommendations proposed in the *Insights* could lead to useful development of good and harmonised practices that increase the relevance and robustness of the results. The OECD Network on Agricultural TFP and the Environment provides an opportunity for continuous exchanges on methodological and analytical research. In particular, academics can help clarify concepts and new estimation methods for shadow prices of desirable and undesirable by-products. This can help adapt traditional TFP measures to environmental issues while maintaining a transparent approach through synthetic index numbers. The Network could also be used to bridge communication between academic work and the needs of the policy debate, for instance on global public goods such as GHG emissions.

The OECD has also developed a set of agri-environmental indicators that allows assessment of the environmental performance of the agricultural sector. Traditional TFP measures can be discussed together with indicators of the environmental performance of agriculture in order to have a more comprehensive discussion of the sectoral performance. This is a promising avenue to advance in measuring performance using alternative sets of indicators. The combination of indicators that jointly evaluate productivity and environmental performance shows potential to analyse policy linkages. For example a high livestock density and thus manure intensity increases GHG emissions and nutrient surplus and consequently hinders achievement of good productivity performance (Lankoski and Thiem, 2020[50]). One difficulty is the ambiguous message that different, equally reasonable indicators can carry. For instance, regarding the interpretation that different indicators focused on pollution intensity (per production vs. per hectare) compared to the absolute level of pollution might convey. Efforts to construct graphical analysis and composite indicators of sustainable productivity growth have been carried out (OECD, 2021[51]; OECD, 2021[21]), and others are under way. They show that it is possible to build composite indicators that are useful for both benchmarking and policy analysis.

Potential role for the OECD

Building on the efforts undertaken by national and international agencies on existing databases, and on the experience of the TFP Network, the OECD could play a significant role in guiding best practices and standards or, possibly, hosting harmonised data for total factor productivity (TFP) measurement. The purpose would be bridging knowledge between researchers, statistical agencies and policy makers on the adjustment of TFP for environmental outcomes.

The OECD could also foster new developments and analysis based on growth accounting analysis that are potentially of great value to policy makers. There is a need to promote the use of productivity analysis for policy assessment and design. Applied analysis could include different sources of growth, the analysis of causes and effects such as the determinants of TFP gains (e.g. R&D), and the sharing of productivity gains along the supply chain.

Finally, thanks to the OECD Networks on Agricultural TFP and the Environment and on Farm Level Analysis, as well as the unique investment in agri-environmental indicators, the OECD can promote a diversified approach and alternative options for measuring sustainable productivity growth. This includes the calculation of environmentally adjusted TFP, the combination of TFP with agri-environmental indicators, and the use of other sources of information such as farm level data. Theoretical findings and new methods can be tested empirically on a larger scale, facilitating the comparison of results across countries and its interpretation for policy purposes.

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This report was declassified by the Joint Working Party on Agriculture and the Environment in May 2022 and was prepared for publication by the OECD Secretariat.

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