G20 MACS White Paper:

Metrics of Sustainable Agricultural Productivity

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Executive Summary

1. Raising agricultural productivity can improve economic welfare, strengthen food security and conserve environmental resources. Since agricultural productivity is strongly influenced by policies, institutions, socio-economic forces, and environmental conditions, metrics of agricultural productivity provide a means of evaluating the effects of these factors. Most existing metrics of agricultural productivity, however, do not fully account for the use of environmental goods and services in agricultural production, thus provide only a limited means for assessing the long-term sustainability[1] of agricultural productivity growth.
2. Productivity metrics are a quantity-based output/input ratio of a production process. Main classes of productivity metrics include partial factor productivity (PFP), total factor productivity (TFP), and total resource productivity (TRP).[2] PFP measures output per unit of one input and is the simplest and most widely used productivity metric. TFP is a ratio of the total marketable outputs to total marketable inputs in a production process. TFP provides richer information than PFP on economic efficiency, but does not include environmental inputs or outputs that are not priced in the market place. TRP extends TFP to include non-market environmental goods and services used in agricultural production. Few empirical applications of TRP currently exist, however. Moreover, none of these metrics address important dimensions of ecological sustainability, such as resilience.
3. Total Factor Productivity (TFP) is a widely used measure of economic performance. Applied at the level of the firm, economic sector, or whole economy, TFP is designed to measure the efficiency with which economics resources are used to produce economic outputs. TFP is measured as an index relative to some base period or location, and the units of TFP

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[1] The concept of sustainability adopted here reflects the definition employed in the Brundtland Report (1987): *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* A more operational definition of sustainability is presented in Section IV of the White Paper.

[2] Crop yield per hectare and value-added per worker are common examples of PFP. Empirical estimations of TFP is sometimes called multi-factor productivity. The OECD refers to TRP as "environmentally-adjusted TFP". TRP is closely related to "green growth accounting" that seek to include valuation of environmental goods and services in national economic growth statistics.

measure the percent difference with the base. The rate of growth in TFP is often interpreted as the rate of technological change. Indices of agricultural TFP provide the best currently available means of assessing progress toward sustainable agricultural productivity at the national or regional level.

4. Agricultural TFP indices have been estimated for most countries but due to differences in methodologies and data quality it is difficult to make cross-country comparisons. At present, there are two broad quality tiers of agricultural TFP available – the first tier meets high international standards for economic productivity accounting and enable accurate cross-country comparisons; the second tier provides less refined TFP indices due to incomplete agricultural statistics and give only an approximate measure of TFP growth. The first tier is currently available only for a few high-income countries, while the second tier is available for most other countries. Formalizing international collaboration to harmonize methods used for constructing agricultural TFP indices could strengthen and expand efforts to construct up-to-date, accurate and internationally comparable indices of agriculture TFP.
5. Since TFP does not fully account for the use of natural and environmental resources in production, it needs to be supplemented with other measures in order to assess sustainability of agricultural production. One approach is to develop sets of agri-environmental indicators and track trends in these indicators alongside TFP. Another approach is to extend TFP to explicitly include environmental goods and services along with market-based goods and services, into a broader index of TRP. The advantage of TRP is that, by valuing environmental goods along with market goods, potential economic and welfare tradeoffs between these outcomes are explicitly considered.
6. To date, comprehensive sets of agri-environmental indicators and TRP indices are not available. While there remains considerable uncertainty regarding how and what environmental goods and services should be included and how they should be valued, progress has been made in recent years in assembling preliminary sets of agri-environmental indicators and developing methodologies for measuring TRP. The OECD project on agri-environmental indicators is probably the most advanced efforts to date. Nonetheless, agricultural TRP indices that may be developed over the next several years are

likely to be selective in their inclusion of natural resource and environmental, due to both scientific and data constraints and limitations.

7. For a comprehensive assessment of sustainable agricultural productivity, there remain important gaps in fundamental scientific understanding of the relationship between agriculture and the environment. Considerable uncertainty remains regarding basic questions such as: how much soil loss can be sustained before agricultural yield is comprised? What is the relationship between changing biodiversity and long-term agricultural productivity growth? What is the appropriate scale (field, land-scape, regional) for assessing ecological relationships in agriculture? Is more efficient agricultural production also more resilient? Without better scientific understanding, we cannot be confident that any proposed metric of sustainable agricultural intensification actually achieves its goals. Continued and enhanced support for fundamental research on sustainable agricultural systems will enable the development of improved productivity metrics at the appropriate scale.
8. In the future, use of new data tools, like remote sensing, and related bio-physical and ecological models may significantly reduce the cost of real-time and spatially-disaggregated assessment of the status of environmental resources used or affected by agriculture. This could contribute to construction of indices like TRP.

I. Introduction

When the G20 Meeting of Agricultural Chief Scientists (MACS) convened its first meeting in Mexico in 2012, accelerating sustainable intensification of agricultural production to achieve long-term, global food security was high on the agenda. Subsequent meetings of the G20 MACS focused on specific shared initiatives to improve coordination and scientific information-sharing among their agricultural research and development (R&D) systems.

At the 2014 MACS in Australia, the issue of performance measures for sustainable agricultural intensification was discussed. The Australian delegation reported findings from a new study of long-term trends in agricultural *total factor productivity* (TFP) for Australia, Canada and the United States. TFP is a well-developed economic concept that is widely used to evaluate the efficiency and productivity of national economies and sectors. TFP compares the growth in the aggregate quantity of output (i.e., the aggregate quantities of crop and animal commodities produced), with the aggregate amount of land, labor, capital and material inputs employed in production. TFP increases when the output from a given level of inputs rises, or, equivalently, when a given level of output is produced using fewer of these inputs. While TFP fluctuates from year-to-year due to the influences of weather and other factors, the longer-term trend in TFP provides a measure of the rate of technological change.

While there was general interest in agricultural TFP at the 2014 MACS as a possible metric for sustainable productivity, questions were raised about the availability, comparability and timeliness of estimates of agricultural TFP in G20 and other countries. Another concern was how TFP treated natural resources and environmental goods and services related to agricultural production. If agricultural yields or TFP are being raised at the expense of environmental resources, such as water quality, soil health, and biodiversity, then it may be missing some essential dimensions of sustainable intensification.

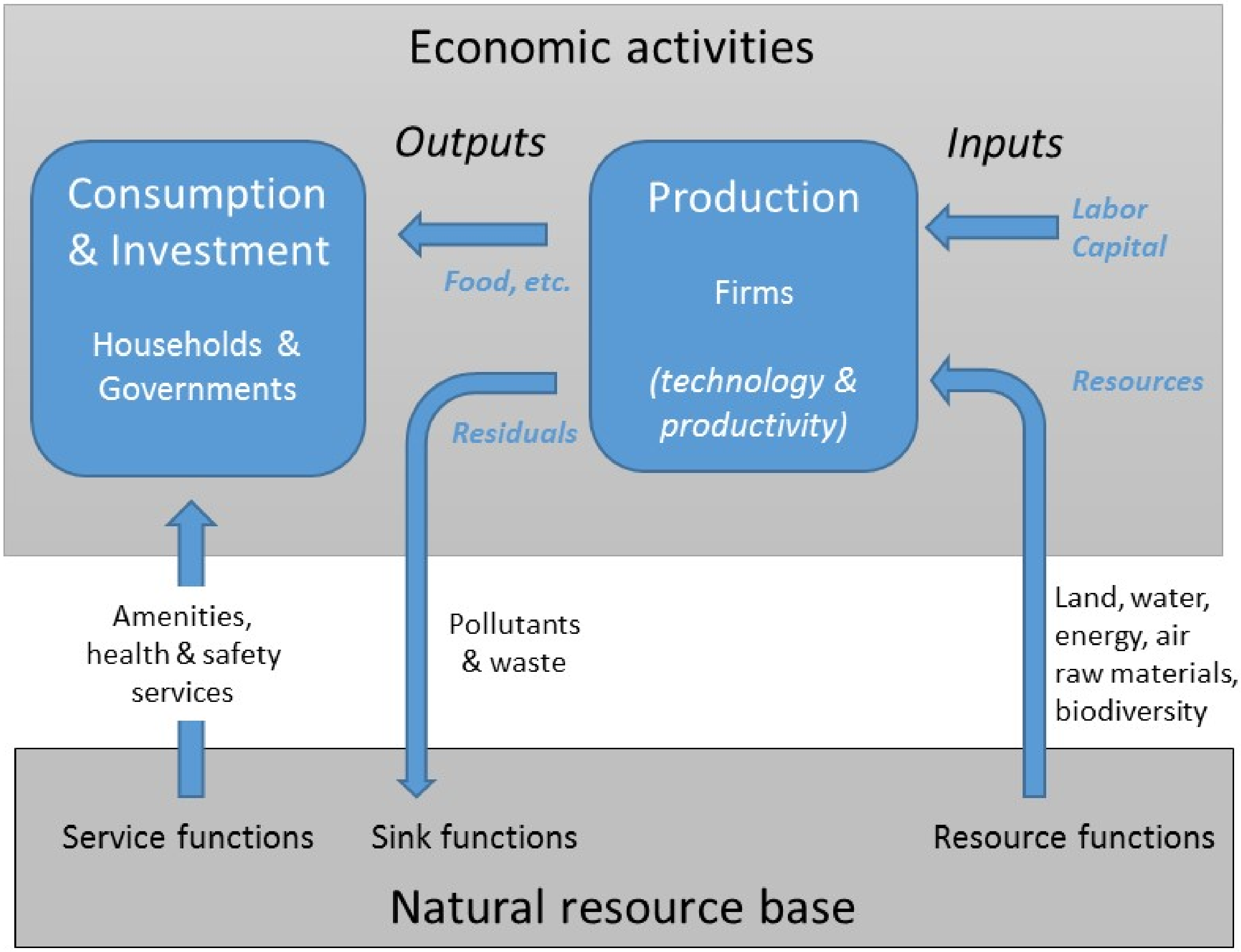
Following the presentation and discussion, the MACS formed a Working Group to review the status and availability of TFP, and assess whether it or some other measure or combination of measures would be informative for assessing progress toward sustainable agricultural intensification. This White Paper reports the findings and recommendations of the Working Group. The report focuses on two principal issues:

i. Regarding agricultural TFP, what is the status, quality, and comparability of existing TFP measures, and how might these be improved through support from the MACS?
ii. What additional metrics may be necessary for assessing how natural and environmental resources are affected by agricultural production and productivity?

Other social dimensions of sustainable agricultural systems, such as equitable rural development and the food and nutritional security of households, are not addressed in this report.

The general framework adopted by the Working Group for considering both economic and environmental goods and services in a measure of productivity is depicted in Figure 1.1. *Productivity* is defined as how well an economic system converts inputs into outputs. Inputs into agricultural production include labor, capital, and resource inputs such as land, water, and biodiversity, and material inputs (energy, fertilizer, chemicals) derived from raw materials. The outputs from production include agricultural crop and livestock commodities, other agriculture related services and also unintended by-products that return to the environment, such as greenhouse gas (GHG) emissions and chemical, nutrient and sediment loadings to water bodies. Many of these by-products are pollutants that impose a social cost by reducing the supply of environmental goods and services available for other uses. Some by-products may also have positive environmental functions, like sequestered carbon in agricultural soils.

Figure 1.1 Framework for measuring productivity with economic and environmental goods



Note to Figure 1.1: In production, firms combine labor and capital with resources to produce outputs for consumption and investment. Pollutants and waste are production residuals that may degrade the natural resource base. In addition to providing resources for production and a sink for pollutants and waste, natural resources provide other environmental services, such as recreational and scenic amenities and health and safety services such as flood control, climate stabilization and biodiversity habitat. Total-factor-productivity (TFP) is a measure of the efficiency with which labor, capital, resources are converted into outputs, using producer prices or opportunity costs to aggregate inputs and outputs. Total-resource-productivity (TRP) is a measure that extends TFP to include environmental resources and output residuals. Since market prices may not fully value these services (if at all), for the purpose of constructing TRP they may be valued at their user abatement cost or social opportunity cost.

Source: OECD (2011a).

A measure of the productivity of this production system compares the amount of one or more of the outputs to one or more of the inputs. ***Partial factor productivity*** (PFP), like crop yield per hectare or value-added per worker, compares one or a group of outputs to one input. ***Total factor productivity*** (TFP) measures the ratio total marketable outputs (crop and livestock commodities) to marketable inputs (land, labor, capital, and materials), but does not take into account inputs and outputs that do not have economic value to the producer. ***Total resource productivity*** (TRP) attempts to extend TFP to include environmental goods and services (the resource and sink functions in Figure 1.1) that aren’t valued by the market. While market prices or private opportunity cost derived from market-based values are typically used to aggregate outputs and inputs in constructing TFP, non-market valuation methods are required to derive comparable “shadow prices” or social opportunity costs of environmental goods and services for the estimation of TRP.

The next section of the paper reviews the basic concepts of agricultural TFP, describes general challenges in measuring agricultural TFP, and calls attention to an international collaborative project to compare agricultural TFP among Australia, Canada, the United States, and members states of the European Union, using best practices from economic science (labeled the ‘gold standard’ in the White Paper). A more extensive review of international comparisons of agricultural TFP that includes other countries is provided in the Appendix. Section III reviews efforts to assemble agri-environmental indicators and develop indices of TRP, which extends TFP to include environmental goods and services. While including environmental factors in TFP faces significant methodological and empirical challenges, efforts by the OECD and the United Nations are working toward this goal. Finally, section IV of this report calls attention to the need for further research to more fully understand interactions between agriculture and the environment. There are important and critical knowledge gaps on long-term implications of resource use and the resilience of agricultural systems, particularly where “thresholds” may exist in environmental degradation past which production of agricultural and ecosystems services is no longer viable.

II. Productivity Metrics in Agriculture

Agricultural productivity measures the ability of a production unit (i.e. field, farm, or industry) to convert economic and natural inputs into desirable outputs. Broadly speaking, it can be defined as a ratio of a measure of output to a measure of one or more inputs used in the production process. While there is a general consensus about the broad notion of productivity, disagreements remain on the interpretation of productivity estimates and the choice among various measurement methods. This section discusses the concept and interpretation of productivity metrics. It gives particular attention to how agricultural TFP is measured, the availability of cross-country agricultural TFP comparisons, and the usefulness of agricultural TFP as a tool in policy analysis.

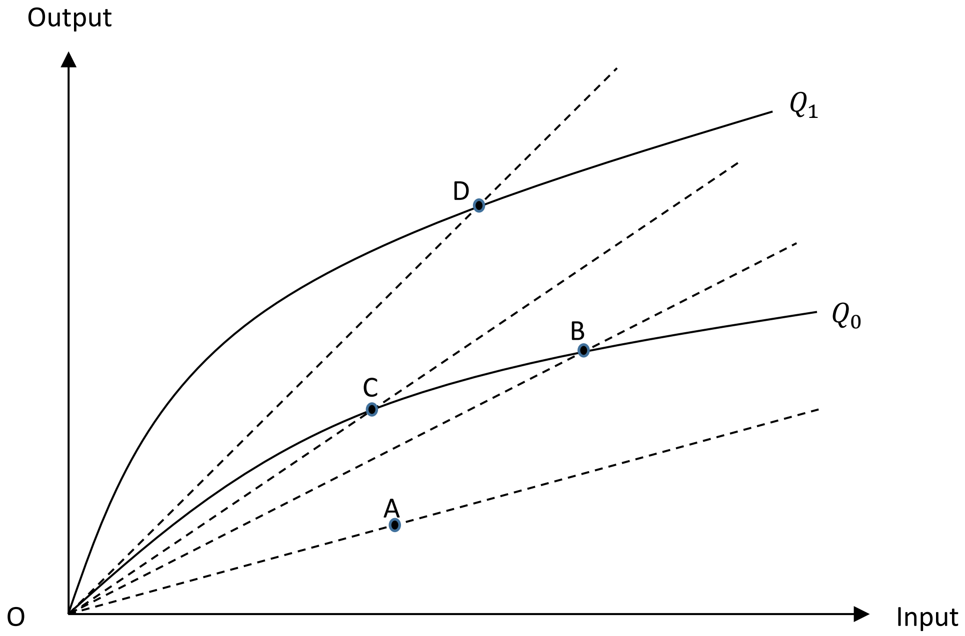
A. Concept and Interpretation of Total Factor Productivity

The most common interpretation of TFP is that it represents the status of technology and efficiency in production and, when it is expressed as change, it measure technological progress (Jorgenson et al. 2005). More precisely, TFP measures a specific technology associated with a production process that generates beneficial outputs net of the contribution of inputs. TFP may be used to identify real input or cost savings and to assess relative economic welfare (OECD 2001).

Both TFP levels and its growth are useful indicators. For example, one can compare the TFP levels of individual economic units (for example, productivity differences among farms, industries or between countries or regions) at a particular point in time to infer differences in the level of technology. Similarly, when expressed in terms of a change over time, TFP growth can be interpreted as a measure of technological progress of that farm, industry, or region.

To illustrate how TFP levels and its growth are derived, we start with describing in Figure 2.1 the technical relationship between output and input. In economics, this refers to the production function, which suggests that output changes with input and the two variables are positively related (shown by the curves Q_0 or Q_1 in Figure 2.1). Based on the production function, a TFP level is thus defined as the slope of the line going through the origin (O) and a production point such as A, B, C or D. The greater the slope, the higher the average TFP, which implies that more output is produced by using the same or less amount of input. A change in TFP level (or TFP growth) is thus caused by: 1) a shift in the production function which, in Figure 2.1, is represented by a shift in the profile from Q_0 to Q_1 (from B to C, or technological change); or 2) a movement along or away from the initial production function and, in Figure 2.1, it is represented by from B to D or a movement from A to B. Note that in Figure 2.1, the movement from A to B represents an efficiency change, since A lies below the production function frontier Q_0, implying that using technology Q_0 more output could be produced using that level of input.

Figure 2.1 Simple illustration of what "productivity" measures



Note to Figure 2.1: The solid lines Q_0 and Q_1 represent different production technologies – the rate at which inputs can be transformed into outputs. Their curvature implies diminishing returns. The shift in the production function from Q_0 to Q_1 represents technological change (more output is possible from each level of input). Points A,B,C, and D are input-output choices that represent rising levels of productivity. Productivity is the ratio of output to input, which is shown by the slope of the dashed lines. Points on a production function (B and C on Q_0, and D on Q_1) are technically efficient given the technology, while points below the production function (A) are technically inefficient.

In addition to TFP, there are many other productivity measures. The choice between them depends on purpose of use and, in many instances, on the availability of an appropriate methodology and data. One of the most important alternative productivity measures is the partial factor productivity (PFP) measures such as yield and labor productivity.

Comparing the two types of productivity measures, PFP measures are simpler to calculate and more intuitive to understand. But they are of limited use for summarizing the overall productivity performance of the production unit. This is partly because PFP measures — defined as a ratio of total outputs and a single input — can result in a misleading assessment of productivity performance if there is input substitution taking place. For example, yield is a measure of output per unit of land used. Holding the use of land constant, yield is likely to increase if the use of labour, capital or intermediate inputs increase. In this situation, additional output comes as a result of increase in other inputs rather than technological progress or efficiency gains. Hence, statistical agencies prefer productivity measures like TFP, which accounts for all the major inputs within the production process, such as land, labor, capital, and intermediate inputs. It offers a more comprehensive picture.

It should also be noted that the terminology of multifactor productivity (MFP) is sometimes used to represent the concept of TFP. This is because many economists and statisticians hold a view that in practice one can never exhaustively include all outputs and inputs (including environmental goods and services) in the calculation of TFP. Thus, the best one can achieve is the inclusion of multiple rather than all factors of production. However, many studies use the term TFP to represent both the theoretical concept and its empirical application.

In this paper we refer to TFP as both the concept as well as empirical applications where most, if not all, economic variables used in production have been included. Moreover, by extending the concept of TFP, it is straightforward to arrive at a new concept of total resource productivity (TRP) to represent a productivity measure that includes non-market goods and services (i.e. environmental inputs and by-product pollutants) in the productivity calculation (Gollop and Swinand 1998). In this way, the two distinct concepts -- TFP and TRP -- can be easily related, and analyzed and compared in a transparent manner.

As previously mentioned, the productivity measures described above are usually referred to as indicators of the level of technology, broadly defined. More specifically, TFP and

TRP represent the outcome of myriad changes in how farming is conducted and organized. Short-term or cyclical fluctuations in productivity are also influenced by weather events and business cycles. Long term trends in productivity can be affected by only on adoption of improved inputs or new farming methods but also structural changes in agriculture. The exit from farming of less efficient farms, or the growth of larger farms that can achieve economies of scale, would raise the average productivity of the industry. Productivity is also determined by how well farmers manage current technology, which is often correlated with accumulation of human capital (i.e., better educated and more experienced farmers). Some studies attempt to explicitly measure changes in the quality of farm labor when deriving TFP, so that improvements in human capital is treated as another factor of production (part of measured inputs) and not part of TFP.

In turn, the producer decisions that lead to improvements in technology and efficiency are themselves influenced by external factors like agricultural, trade and macroeconomic policies, market forces, and consumer preferences. Changes in environmental conditions, and how producers adapt to them, also affect measured levels of production (See Box 2.1: Climate Change and Its Impact on Agricultural TFP Estimates). In section II.C below we describe in more detail on how external factors, especially policies, influence agricultural productivity and how productivity indicators can be used in research and analysis to assess the drivers and determinants of productivity and productivity changes.

Box 2.1 Climate Change and Its Impact on Agricultural TFP Estimates

Technological progress and changing climate conditions (in particular, droughts) have long been regarded as the two important factors determining the growth of TFP in global agricultural production. However, identifying and separating the relative impact of technological progress on TFP from that of climate factors is a challenging task, from both a theoretical and empirical perspective. This is partly because climate change not only affects agricultural TFP directly through its impact on outputs and inputs but also influences farmers' behavior in adapting to the change.

Empirically, many studies have shown evidence of the change in climate conditions on agricultural TFP. For example, Sheng et al. (2010) show that frequent droughts (namely, 1993-94, 2002-03 and 2005-06) have significantly contributed to the slowdown in TFP growth of Australian broadacre agriculture after 2000. Beddow and Pardey (2015) who attribute 16-21% of the growth in US corn yields between 1879 and 2007 to spatial movement in production, as farmers concentrated production in regions of the country most environmentally suited for growing corn.

To account for the impact of climate change, the OECD Secretariat organized the Expert Workshop on Measuring Environmentally Adjusted Agricultural Total Factor Productivity and Its Determinants (in December 2015). The workshop explored the feasibility of measuring agricultural TFP for OECD and G20 countries, with an intent to achieve statistical comparability and policy relevance. The workshop proposed establishment of an OECD-led network of experts from relevant countries and organizations to develop protocols for data and technical specification that could be used to calculate the environmental adjusted TFP for agriculture.

The above studies suggest how TFP estimates in agriculture (in particular, the non-irrigated agriculture) are jointly determined by technological progress and climate conditions.

B. Availability and Status of TFP Measures

Approaches for measuring TFP fall into two main classes: parametric and non-parametric (Griliches 1996). The parametric approach involves econometric modelling of production functions and often uses regression techniques to estimate the relationships between total output and major types of inputs, like land, labor, capital, and intermediate inputs. Once the output that can be attributed to the inputs is determined, the residual (unexplained) output from these regressions can be used as a measure of TFP. One of the major non-parametric approaches is "growth accounting", in which output and input prices are used to aggregate quantities to form a ratio of total output to total input, which is defined as TFP (Caves et al. 1982, Diewert 1992). This is the basis for constructing Törnqvist-Theil (or simply "Törnqvist") and Fisher Indices (described below and in the Appendix). Another non-parametric approach, often used when price information is unavailable, is "directional distance functions" (i.e. the Malmquist index) in which linear programming solutions are used to trace out a productivity frontier using only quantity-based data. The distance of a country or farm to the frontier and shifts in the frontier over time define a productivity index (Färe et al. 1994, Coelli and Rao 2005).

Growth accounting-based indices are used by many national statistical agencies to estimate economy-wide and sector-level TFP (see for example, Australian Bureau of Statistics 2007, Bureau of Labor Statistics 1983, and OECD 2001). Because of its strong theoretical properties and empirical robustness, the Törnqvist index (or the closely related Fisher Index) is probably the most popular method for measuring TFP. In fact, efforts to standardize TFP indices for the purposes of international comparisons led to the formation of the WORLD KLEMS Consortium in 2010, which draw membership from national statistical agencies and academic researchers (see Box 2.2: International Productivity Comparisons: WORLD KLEMS and Agricultural TFP). While WORLD KLEMS has not made much progress in constructing robust measures of agricultural TFP (it focuses more on TFP in manufacturing and service industries), it does provide a model of how international collaboration in productivity measurement can lead, over time, to better and more harmonized TFP indices among countries. The next section of the paper describes the present status of international comparisons of agricultural TFP using growth accounting and how they are used in policy analysis. We label the Törnqvist Index as the "gold standard" approach for measuring TFP.

Box 2.2: International Productivity Comparisons: WORLD KLEMS and Agricultural TFP

The World KLEMS initiative (http://www.worldklems.net/index.htm) is the first international collaborative project to build a consistent and harmonized measurement of economy-wide TFP, with the aim to promote and facilitate the analysis of economic growth and productivity patterns around the world. It publishes analytical databases in the consistent format either sponsored by the Consortium or the partner institutions, in addition to provide links related to official statistics published by National Statistical Institutes. Currently data are available for 36 countries. Among the G20 economies, only Saudi Arabia, Indonesia and Turkey are not covered by the KLEMS program to date. India is a participant of KLEMS program but TFP statistics are not yet available.

At the heart of the initiative, the World KLEMS aim to develop new databases (or update the existing datasets) on output, inputs and productivity at a detailed industry level by adding new countries and regions in order to assist academic research and public policy making. To ensure that data is comparable across countries, it proposes a set of harmonized concepts and standards (including input definitions, price concepts, aggregation procedures etc.) and reinforces a global community of practice by organizing workshops and conferences. The most recent release of data was in 2014, and the data released were categorized into three KLEMS-type database: analytical datasets, regional networks and projects, and statistical KLEMS databases published by NSIs.

Under the World KLEMS initiative, agriculture is one of the three pillars (parallel to manufacturing and service sectors) but little progress has been made in data collection and compilation since the first release of EU KLEMS in 2009. As one of the 32 sectors (ISIC Rev. 3), agriculture is included in a larger aggregate: "Agriculture, Hunting, Forestry and Fishing" and does not benefit from a tailored treatment (e.g. no specific consideration for the land as a factor of production). A description of the database and the methodology is available in O'Mahony and Timmer (2009).

To fill the gap, the USDA ERS initiated the Global Agricultural TFP Measurement Group in 2010 and since then agricultural production accounts for 17 OECD countries including the US, Canada, Australia and 14 EU countries between 1973 and 2011 have been gradually developed. For developing countries, the Asian Productivity Organization (APO) organized a five-day workshop in late 2015 in Tehran, I.R. Iran and the purpose was to collect information of inputs and outputs from the official statistical agencies in the 18 Asian developing countries. Meanwhile, the OECD organized an international expert workshop in December 2015 to discuss the possibility to construct a thorough and accurate measure of agricultural TFP between countries.

Despite of progress that has been made, the World KLEMS is calling for more efforts in measuring and comparing agricultural TFP following an international standard through international

1. A “gold standard” for growth accounting: the Törnqvist Index

Conceptually, TFP is the ratio of gross output to total inputs while TFP growth is the difference between the rate of change in gross output and the rate of change in total input.

$$TFP_t = \frac{Y_t}{X_t} \quad (2.1)$$

$$\frac{\Delta TFP_t}{TFP_t} = \frac{\Delta Y_t}{Y_t} - \frac{\Delta X_t}{X_t} \quad (2.2)$$

where TFP_t represents the level of total factor productivity, Y_t measures the total quantity of output, and $X_t$measures all inputs used, at time t.[3] The terms $\Delta TFP_t, \Delta Y_t$, and ΔX_t represent the rates of change of these measures over time. Both TFP level and growth are used to measure technological progress and efficiency improvement. TFP levels, however, are more difficult to estimate than TFP growth, because meaningful comparisons of TFP levels requires much greater attention to the quality and composition of the outputs produced and inputs used in production. It requires, for example, that land, labor and other factors of production be measured in units of consistent quality across space and over time.

Using Equations (2.1) and (2.2) to estimate agricultural TFP level and growth, one needs to aggregate various outputs and inputs in a consistent way. This is because, in agriculture, output is composed of multiple commodities produced from multiple inputs in a joint production process and the composition of outputs and inputs is changing over time. A common practice is to sum over outputs and inputs using the corresponding prices (or revenue/cost shares) as weights based on an index formula (Diewert 1992).[4] For cross-sectional or trans-temporal comparison, an index measure will thus be formed when a benchmark (i.e. a base country or a base year) is chosen.

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[3] Empirically, TFP has two variants – one based on gross output and one based on value-added. The gross output variant measures the ratio of total gross output to the total labor, capital and intermediate inputs (including energy, materials and purchased services). The value-added variant measures the ratio of value-added (gross output net of intermediate inputs) to just the total of labor and capital inputs. In sectors like agriculture where new technology is often embodied in intermediate inputs (such as improved seeds and chemicals), the gross output variant is generally preferred (Ball et al. 1997). In this paper, TFP refers to the gross output variant unless otherwise noted.

[4] Under conditions of long-run, competitive market equilibrium, where supply equals demand and producers are price-takers who maximize profits, then using prices as aggregation weights yields an index that represents the level of technology and the rate of change in the index gives the rate of technological change (Diewert 1992). Please refer to Appendix I for detailed technical discussion and index number formulas.

In practice, there are many index formulas that can be used for output and input aggregation, but the Törnqvist index can be considered the “gold standard” for TFP measurement. This is because, compared to other index formulas, the Törnqvist index has a number of desirable properties. First, the index links to a flexible production function and has a clear economic interpretation. Diewert (1992) showed that the Törnqvist index provides a close second order approximation for any arbitrary production function and, under some reasonable assumptions, is an “exact” representation of a translog production function. Second, the Törnqvist index formula performs better than other indices for the construction of productivity indices. As with the Fisher index, the Törnqvist index satisfies 21 reasonable tests — significantly more than any other index, when using the axiomatic test approach (Fisher 1922). Third, the Törnqvist index provides a neat functional form for calculating TFP growth, which simplifies the estimation process and facilitates cross-country and cross-region comparisons.

To estimate agricultural TFP level and growth, both outputs and inputs must be defined and compiled in a consistent way. Since TFP is designed to reflect the efficiency of economic resources used for producing economic outputs, hence outputs and inputs are defined from an economic perspective. Outputs refer to all goods and services that are produced by an agricultural firm or sector, which can be categorized into crops, livestock and livestock products, and other services from agricultural capital (tractor-hire services, for example), while inputs refer to economic resources available to farms, which are categorized into land, labor, capital and intermediate inputs.

Two main data sources — namely, national account statistics and farm census/survey data — are typically used to provide data for TFP indices, depending on the level of aggregation. National economics accounts, either obtained from individual countries separately or from international organizations such as FAO and OECD, provide the output and input data for estimating the agricultural TFP of a country. Farm census and survey data are more flexible in aggregation and thus provide the output and input data for regional-, commodity-, or farm-level TFP.

A shortcoming of the Törnqvist index for measuring agricultural TFP levels and growth is that it requires annual data on quantities and prices of each output and input in sufficient detail so as to make these measures comparable. For example, simply knowing the amount of agricultural land in production is not sufficient if the quality of this land is very heterogeneous (e.g., some if irrigated cropland, some semi-arid rangeland, etc.).

Another typical gap in data is the lack of representative price information for commodity and inputs. One approach to this issue has been to impute price data from other sources, such as using average price data from other farms or countries with similar agricultural systems (Fuglie 2012). Others have used directional distance functions (i.e. the Malmquist index) to estimate agricultural productivity which require only data on output and input quantities (Coelli and Rao 2005). However, the distance function approach is sensitive to aggregation, sample distribution and data quality issues, which can lead to biased and inconsistent TFP estimates.

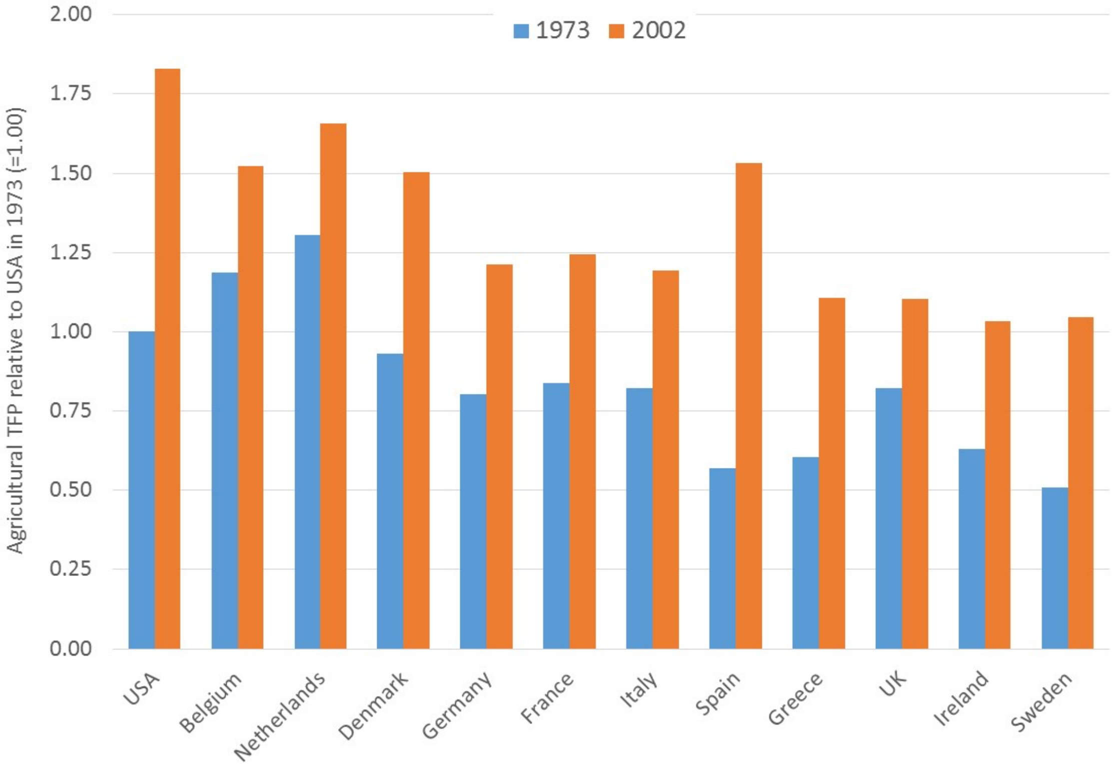
2. International comparisons of agricultural TFP

Globally, agricultural productivity continues to increase as a consequence of ongoing technological progress, industry structural adjustment, and institutional and policy reforms. By one estimate, global agricultural TFP grew at an average rate of 1.0 per cent a year between 1961 and 2012, and was responsible for about half of the global growth in agricultural output during these years (Fuglie 2015). Despite a significant disparity in TFP levels and growth rates among countries, agricultural productivity in the G20 countries has grown more quickly than in the non-G20 countries. In addition to technological progress, changing environmental factors also contribute to inter-country disparities in TFP levels and growth.

Applying the 'gold standard' approach with data from national economic accounts, (Ball et al. 2010) estimated agricultural TFP levels and growth rates for the US and eleven EU countries (namely, Belgium, Demark, Germany, Greece, Spain, France, Ireland, Italy, Netherlands, Sweden and United Kingdom) each year from 1973 to 2002. More recently, Sheng et al. (2015) used this approach to compare agricultural TFP for the US, Canada and Australia from 1961 to 2006. Figure 2.2 shows how agricultural TFP and TFP growth compared among countries, using USA as the reference point.

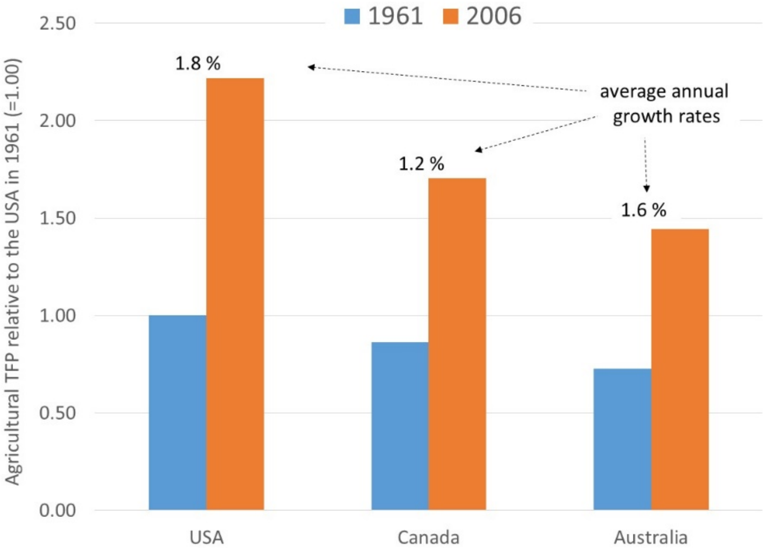
Figure 2.2 Comparison of agricultural TFP among selected OECD countries

2.2a: Agricultural TFP in the USA and EU countries in 1973 and 2002, relative to USA in 1973



Source: Ball et al. (2010).

2.2b: Agricultural TFP in USA, Canada and Australia in 1961 and 2006, relative to USA in 1961



Source: Sheng et al. (2015)

Based on these two studies, at least three important findings relating emerged:

i. ***While agricultural TFP increased rapidly overall, there are significant cross-country disparities***. Between 1973 and 2002, the average agricultural TFP in the US and eleven EU countries roughly doubled for all countries. However, cross-country differences in agricultural TFP remained large: from a base index level of 1.00 for the United States in 1996, agricultural TFP in 2002 ranged from a high of 1.05 in the United States to 0.59 in Ireland. The comparison between the USA, Canada and Australia between 1961 and 2006 illustrates a similar phenomenon. There is little evidence that agricultural TFP in lower-productivity countries in this group were catching up to the countries with the highest productivity levels.

ii. ***Long-term average growth rates in agricultural TFP vary widely among countries, although differences may be small among countries with similar production technologies and initial economic conditions***. In the comparison between the USA and eleven EU countries, the average annual growth rates of agricultural TFP between 1973 and 2002 ranged from 0.74 percent for the UK to 3.05 percent for Spain. In the comparison between the US, Canada and Australia between 1961 and 2006, the average annual growth rates of agricultural TFP were 1.24 percent for Canada, 1.64 percent for Australia and 1.80 percent for the United States.

iii. ***Short-term or annual fluctuation around the long-term trend in agricultural TFP is large, making it difficult to detect changes in the trend growth rate.*** As mentioned in the previous section, TFP estimates not only measure technological progress but also capture the effects of other factors such as changes in climate conditions and natural resources. In particular, changes in soil quality, the availability of precipitation and sunshine, and temperature may lead to different levels of agricultural output over time even if the same inputs are used. For example, frequent droughts after the mid-1990s significantly contributed to the slowdown in agricultural TFP growth in Australia (Sheng et al. 2010).

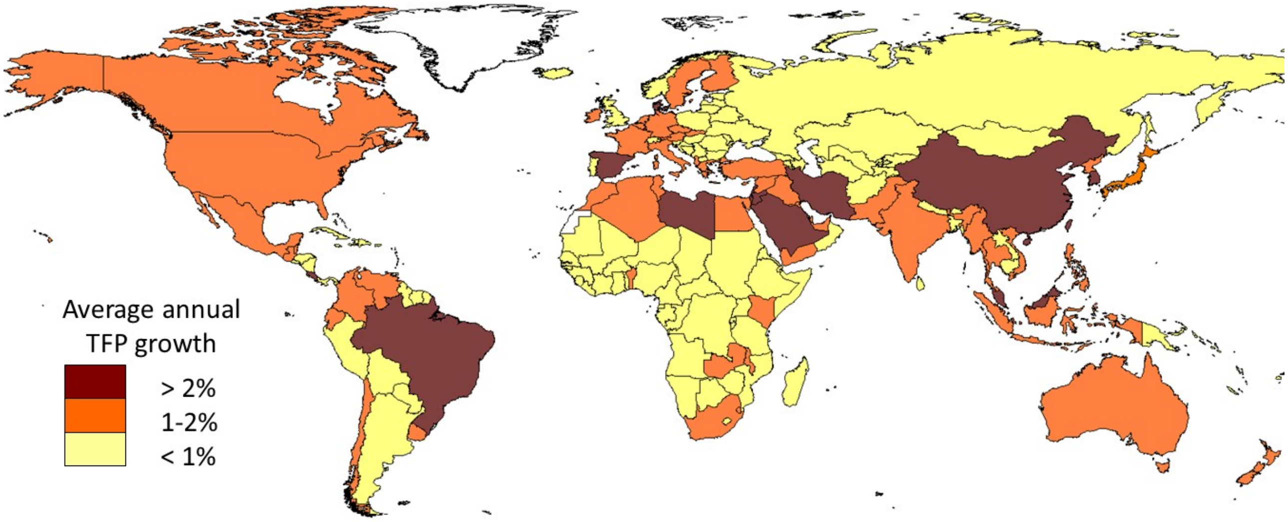
Moving beyond these high-income countries, efforts have been made to apply the “gold standard” method to measure and compare agricultural TFP growth rates (but not TFP levels) among other developed as well as developing countries. These efforts rely primarily on FAO data for estimates of agricultural output and inputs. There are shortcomings in available FAO data for the purpose of TFP measurement (for example, there are no accurate estimate of capital stocks and services and information on input prices is incomplete). Nonetheless, an advantage to these estimates is that agricultural TFP growth is measured in a consistent way for all countries. Fuglie (2012) used this approach to provide a picture of agricultural TFP growth and its distribution throughout the world over the past half a century. These estimates are publicly available on the website of the U.S. Department of Agriculture's Economic Research Service and are updated annually (Fuglie and Rada 2015).

Figure 2.3 depicts the dispersion of average annual growth rates in agricultural TFP over 1961-2012. Most high-income countries have averaged agricultural TFP growth rates of 1-2% per year. Some important agricultural producers like China and Brazil experienced agricultural TFP gates averaging over 2%, while most countries in Sub-Saharan Africa and the former Soviet Union saw only very gradual improvement in agricultural TFP over these five decades. The analysis by Fuglie (2015) also found that globally, agricultural TFP growth accelerated after 1990, although wide disparities remained in national agricultural TFP growth rates. The global average annual agricultural TFP growth rate rose from 0.6 percent in the period 1971-1990 to 1.6 percent during 1991-2012. Agricultural TFP growth in the G20 countries was more rapid than in non-G20 countries, though there are significant disparities across countries.

Appendix Table A1 contains a more extensive list of studies that have developed Törnqvist indices of agricultural TFP for individual countries, including all G20 countries except Turkey and Saudi Arabia.

In sum, a comparison of agricultural TFP among and between G20 countries and the rest of world shows that there are still significant cross-country and over-time disparities in agricultural TFP levels and growth. While many national policies can help explain the differences in long-term agricultural TFP growth, investment and capacities in agricultural research and innovation systems appears to be a key explanatory factor (Evenson and Fuglie 2010). However, year-to-year fluctuation dominates the short-term pattern of agricultural TFP over time.

Figure 2.3 Comparison of agricultural TFP growth rates world-wide, 1961 - 2012



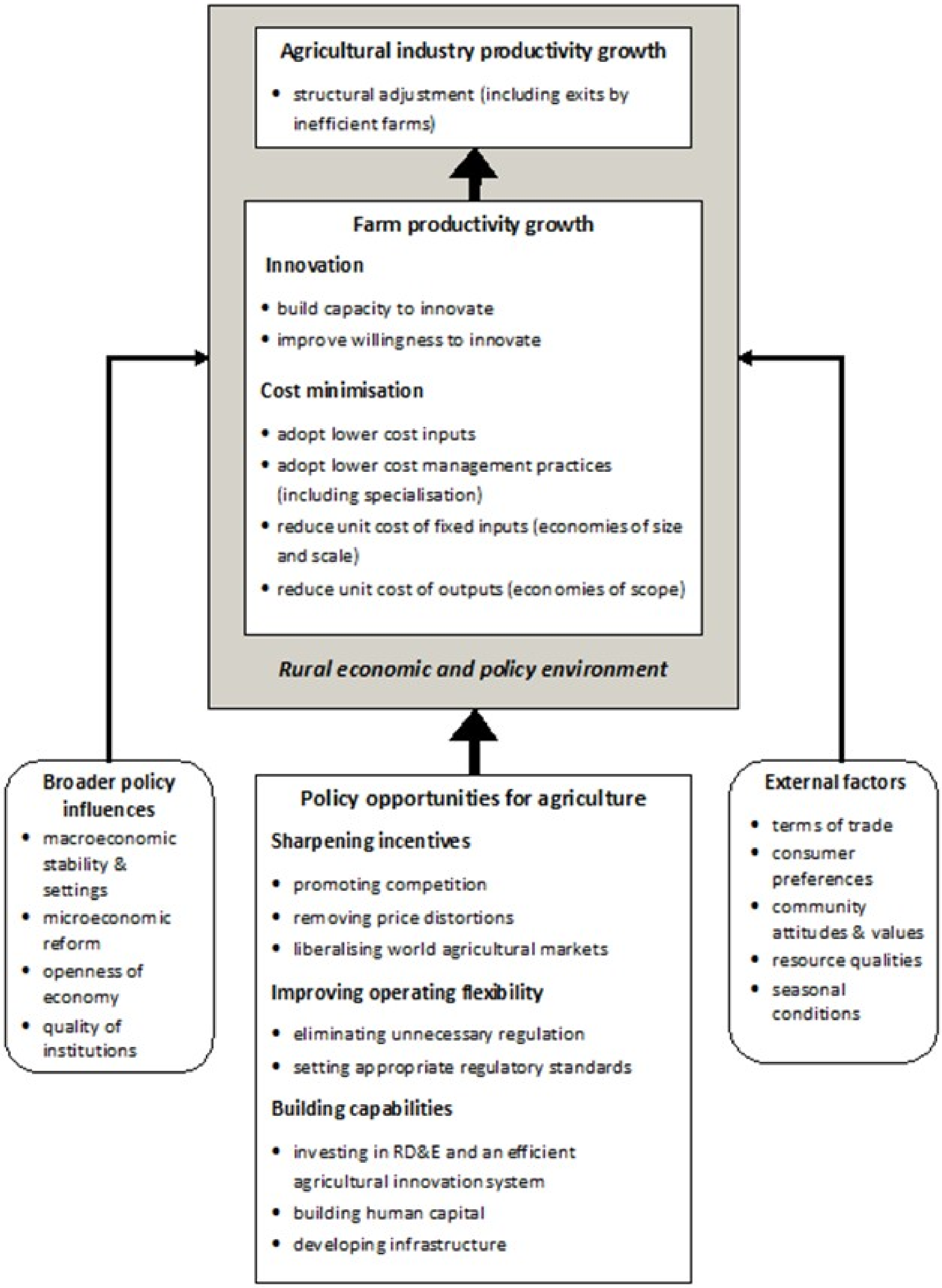
Source: Fuglie and Rada (2015).

C. TFP Analysis and Its Implications for Policy Making

Analysis based on an accurate measure of agricultural TFP at the farm, commodity or national level improves our understanding of the impact of technological change and structural adjustment in the agricultural sector, and the role of policies in shaping these impacts. It also provides useful insights for policy makers in responding to increased and more diversified demands for agricultural products within natural resource constraints. This section discusses the use of agricultural TFP in policy analysis from different perspectives. See Figure 2.4 for a description of some of the key linkages between various policy settings and agricultural TFP.

At the farm and commodity, and national levels, an improvement in agricultural TFP reflects farmers producing more marketable outputs (such as livestock and crops) from using the same or fewer marketable inputs (land, labor, capital, materials and services). Measured at the commodity and sector level, agricultural TFP growth also reflects technological change, more efficient uses of resources, and structural adjustments, including the exit of less efficient farmers. When extended to international comparisons, agricultural TFP can be used to examine the relative competitiveness and comparative advantage in agriculture. It also facilitates the analysis of the effects of different polices and policy changes undertaken by countries.

Figure 2.4 Framework for assessing the causal drivers of agricultural productivity growth



Source: Gray et al. (2014).

A wide range of factors have been identified to influence agricultural productivity at the farm, industry and national levels. There is substantial evidence that R&D investment and on-farm innovation are the main drivers of agricultural productivity growth (Hayami and Ruttan 1985; Evenson and Fuglie 2010). The OECD (2011b) report, "Fostering Productivity and Competitiveness in Agriculture", discusses productivity and competitiveness in agricultural sectors and their determinants, highlighting the role of R&D. It proposes to use agricultural TFP as the key indicator to assess public and private R&D investment policies and their impact on agricultural production.

The existing literature also finds that the level of agricultural TFP and its change over time reflects fluctuations in market prices of outputs and inputs. For example, as the relative prices of farm inputs change over time, profit-maximizing/cost-minimizing farmers opt for lower-cost input combinations. This practice gives rise to substitution and scale effects. Substitution of cheaper for more expensive inputs contributes to productivity growth through cost savings, but could exacerbate over-use of natural resource capital if farmers substitute "free" or under-valued environmental services for market inputs. While some farmers may choose to produce the same output with lower-cost inputs, others may increase their scale of production and use more total inputs — in some instances, through expanding farm size (Sheng et al. 2014). Farmers may also improve productivity by realizing cost savings associated with changes in management and output mix (gains from specialization and scope economies).

In addition, farm and farm manager characteristics are important determinants of productivity growth, insofar as they condition the extent to which farmers are able to innovate. These include characteristics associated with their capacity to innovate or adopt innovations, such as experience, education and training, financial status and attitude towards risk. The relative importance of profit and non-profit objectives may also play a role. This type of information and related analysis provides useful input to deliberations about education and human capital accumulation in rural sectors and the provision of agricultural extension, financial, and insurance services.

At a national level, productivity analysis provides information on the efficiency of resource reallocation between farms and insights about the impacts of institutional arrangements that affect industry structure and adjustment. Improvements in resource allocation are an important source of productivity gains in agriculture. This largely takes place within existing farms, but is also as a result of farms entering and exiting agriculture. In particular, exits of less efficient farm businesses release scarce resources for use by more efficient farms, which are able to expand and increase productivity, increasing the efficiency of resource use in agriculture as a whole.

A large number of studies have investigated the contribution of resource reallocation arising from structural adjustment within agriculture to aggregate productivity growth. For example, Duarte and Restuccia (2010) examined the role of sectoral labor productivity in explaining the process of structural transformation — the secular reallocation of labor across sectors — and its effects on the dynamics of aggregate productivity across countries. Kimura and Sauer (2015) used farm-level TFP estimates to examine and compare dynamic productivity growth in the dairy industries among Estonia, the Netherlands, and the United Kingdom and link the cross-country disparity in TFP to resource reallocation due to country-specific policies and institutions. McBride and Key (2013) examined how the rise of production contracts and farm size affected TFP in U.S. hog production and found positive effects on TFP from both developments. Recently, Sheng et al. (2016) examined cross-farm resource reallocation effects in Australian broadacre agriculture by decomposing aggregate TFP growth and found that structural adjustment and the resulting resource reallocation between farms has accounted for around half of industry-level agricultural productivity growth over the past three decades.

Broader policy influences from across the economy are also important in creating conditions conducive to productivity growth, and thus agricultural productivity analysis based on cross-country comparison can assist policy making at the macroeconomic level. For example, openness to trade and investment can increase the transfer of knowledge and technology between countries and, in effect, facilitate access to the outputs of foreign research and development (R&D). In addition, agricultural productivity growth may depend on the extent to which domestic policies distort or facilitate resource reallocation and adjustments in the structure of production in an economy. As such, identifying the relationship between those factors and agricultural productivity growth is essential for shaping appropriate macroeconomic settings and institutional architecture (such as the rule of law; workplace bargaining arrangements; corporate governance; science, technology and innovation systems; and education and training systems).

The economic effects of many other factors that are beyond the control of farmers and government can also be identified through productivity analysis. Changes in consumer preferences and incomes, resource qualities (such as labor and natural resources), and seasonal conditions can drive profit-maximizing farmers to adjust their input or output mix. These adjustments have implications for productivity, competitiveness, and resource use. The effects of various external factors can vary widely. Shifting community expectations and attitudes towards certain farming practices and technologies, for example, may present opportunities for new innovations and product differentiation. Or, they may lead to government regulation or other policy responses that may constrain farmers' capacity and willingness to innovate.

Productivity analysis based on accurate measurement of agricultural TFP is critical to identifying areas for improving agricultural policies that have potential to influence agricultural productivity growth in the long term. These include building capabilities, such as investing in R&D (to increase the supply of innovations), education and training (to increase farmers' capacity to innovate and adopt innovations) and provision of farm extension and financial services (to encourage adoption of innovations). Decision-makers can also promote productivity growth by ensuring policy settings do not distort farmers' incentives or impede ongoing resource allocation in the sector, through continued micro-economic reform in agricultural input and output markets, and ongoing efforts to reduce unnecessary regulatory burdens.

D. Issues with Existing TFP Measures

While existing TFP measures provide useful information for analyzing technological progress so as to assist policy making, there continues to be room and need for standardization and improvement regarding methodology and data. This is especially important for harmonization of TFP estimates across countries. Three important areas were agricultural TFP indices can be strengthened include (i) adjustment input and output quantity measures for quality differences, (ii) measuring agricultural capital stocks and the capital services flowing from these stocks, and (iii) maintaining consistency in aggregation at different scales. These three issues are discussed below not only because they matter for improving the accuracy of conventional agricultural TFP estimates but also because the discussion helps to provide insights on how statistics from economic accounts could be combined with agro-ecological information to produce a TRP metric.

1. Adjustment for output and input quality

TFP measurement requires inputs and outputs to be measured accurately and consistently. In practice, available measures of these quantities are often composed of multiple products of different qualities. To the extent possible, a good productivity measure should account for differences in the quality of outputs and inputs and how quality changes over time. This is particularly important for dealing with the natural resource inputs like land, whose quality depends highly on the agro-ecological environment. For example, services to agricultural production from cropland usually differ significantly from those from pasture land. Moreover, differences in land quality and attendant changes over time (such as average rainfall, soil type and the proportion of irrigated areas) will affect productive capacity. Not properly accounting for quality differences, especially of agricultural inputs, may generate biased estimates of TFP levels and growth and wrongly attribute changes in TFP estimates (which are caused by changing environmental conditions) to technological change.

The general methodology used for TFP estimation should have the capacity to capture quality differences, if the necessary data on specific outputs or inputs are available. One approach to accounting for difference in quality is to disaggregating the measure into finer and finer units. Measures of agricultural labor, for example, have divided the labor force into several classes based on education, experience, and gender, assigned productivities (based on observed wages) to each class, and then account for how the composition of labor changes over time (Ball et al. 2015). Another approach is to determine how the price of input is related to its characteristics. Cropland, for example, has been valued based on its soil properties, topology, rainfall, whether it is irrigated or not, and other characteristics. As the special distribution of cropland changes over time, these relationships are used to estimate how the average quality of cropland is changed in order to measure total cropland in a constant quality unit (Ball et al. 2010).

2. Valuing the “flow” of services from “stock” variables

For productivity analysis, another challenging task is to derive service ‘flows’ from their related ‘stock’ variables. Examples are agricultural land and capital. The flow of services from the stock of agricultural land is approximated by its annual rental value. These services reflect the lands natural fertility determined by soil and climate. Land is usually treated as a non-depreciating asset, although if soil is eroding at a rate that will reduce its future productivity, the loss of future output should be reflected in the current price paid for land services.[5] Agricultural capital is the accumulated stock of machines, tools, buildings, and land improvements (irrigation, tiling, fencing, etc.) from past investments, with older investments appropriately depreciated for wear. What actually contributes to productivity in any one year is the capital services from this stock, such as what a farmer might pay for tractor hire services if these services are rented rather than owned. Since capital services (rather than capital stock) constitute the actual input in the production process they should be measured in physical units (OECD 2001).

However, while land rental rates can often be observed or imputed, capital services are less likely to be directly observable or measurable. To deal with this issue, economists often approximate them by assuming that service flows are proportional to the ‘productive stock’, which is the sum of capital assets of different vintages after adjusting for ‘retirement’ (the withdrawal of assets from service) and ‘decay’ (the loss in productive capacity as capital goods age), and converting quantities to a standard ‘efficiency’ unit. The proportion is usually determined by an expected or real rate of return to investment, or in other words, the rental rates. The approach is called the perpetual inventory method (PIM).

A similar approach has been used to construct the stock of cultivated biological resources, which include orchards, plantations, vineyards and breeding livestock, and derive their services as a proportion of this stock. In principle, the same logic could be further

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[5] But in practice farm land prices and rental rates may not fully reflect future environmental services from agricultural land, especially if current farm practices are “mining” this resource. For example, the effects of soil erosion on future productivity are gradual and hard to measure or predict. Thus, farm land prices may be based largely on extrapolating its present productivity indefinitely into the future, ignoring the cost of erosion on future productivity.

extended to account for services provided by natural resource stocks, like biodiversity and withdrawals from nonrenewable groundwater resource, and their effects on agricultural TFP.

3. Scale issue and consistency in aggregation

Scale- or context- issues, defined either from the spatial perspective or from the industry coverage perspective, and dominate in many facets of agricultural production and agro-ecology. To reflect these issues in productivity measures, agricultural TFP levels and growth are often estimated at different aggregation levels (i.e. farm, region, commodity, or country). In doing so, data on outputs and inputs (if initially collected at the commodity or the farm levels) can be re-organized and aggregated into other categories of interest. The results should always be consistent in aggregation, since the production technology is assumed to exhibit constant returns to scale and therefore TFP estimates can be viewed as scale independent.

When extending the TFP estimation to include environmental factors, scale issues become more problematic. In fact, many environmental factors are highly scale dependent, affecting productivity differently whether they are measured at the field or landscape level. For example, a flower margin to attract pollinators might be associated with a higher level of pollinator services supplied to that field, but may simply be attracting pollinators from the wider landscape and not contributing to wider habitat improvement necessary to improve population viability (see Section IV.D for further discussion of this issue). More often, landscape- and neighbor-contexts mean that farm-level and landscape level outcomes are not well correlated. More generally, when the activities on one farm produce “externalities” (they affect the performance of activities on other farms), it may complicate consistency of TFP estimation across scales of production.

III. Incorporating Environmental Services into Agricultural Productivity Metrics

In the previous section, Total Factor Productivity (TFP) was described as a ratio between total market outputs and total markets inputs of an economy or economic sector. TFP and TFP growth convey vital information about economic efficiency and productivity growth. Increases in TFP reduce the cost of producing agricultural commodities, and hence, the price of food.

But section II also noted that as a measure of sustainable intensification TFP is incomplete. Agriculture draws upon natural and environmental assets like soil, water, air, and biodiversity, and produces residual by-products like nutrient run-off and GHG that may interfere with other ecological services provided by these natural assets. It is possible for TFP to be growing at the expense of nature. A more complete metric of sustainable intensification needs to take agriculture's effect on natural resources and environmental services into account. We have termed a productivity metric that includes both market-based and non-market (environmental) goods and services as Total Resource Productivity (TRP).

A. Conceptual Issues

TRP incorporates the fact that well-being provided by nature is as important as well-being provided by market consumption. The conceptual approach for measuring TRP is to explicitly recognize that the use of environmental goods and services in agriculture today may mean less of them are available for other purposes, like clean water or future food consumption. Because of their public good nature many environmental services are not valued in the market place. Nonetheless they have significant value for society. The basic approach is to develop measures for the quantities and economic values of the environmental goods and services used in agriculture and include them along with market goods and services to derive TRP.

Efforts to account for nature's value on an equal footing with the market economy are commonly referred to as "green growth accounting" or "green gross domestic product". Tracking TRP over time can not only provide more complete information on sustainable growth but also a means of evaluating the effects of government policies toward this goal.

1. Identifying environmental services

The first step in constructing a measure of TRP is to determine the appropriate units of account. If nature's benefits are to be characterized and tracked over time, then the units must be clearly defined, ecologically and economically defensible, and consistently measured. Like market goods and services, both their quantities and dollar values must be measured. But since many environmental services are shared goods – over which property rights have not been assigned and market transactions do not occur – non-market valuation methods are required to determine prices for these services.

To account for nature's benefits the appropriate units of account are "flow units" – the ecosystem services – and not value of the total ecosystem assets.[6] Ecosystem services are the aspect of nature that society uses, consumes or enjoys to experience those benefits. They are the end products of nature that directly yield human well-being or contribute to production of other goods and services. End products are the aspects of nature that people make choices about. These choices reveal the value that people place on these end products.

It is important to emphasize that many aspects of nature are valuable but are not capable of being valued in an economic sense because they are not easily associated with social or individual choices. While rainfall and sunlight are essential for growing crops, they are not valued in an economic sense because farmers can't choose how much of these natural phenomena to use.

Another important criterion is that an ecological service must be a scarce resource. In other words, if it is used in agriculture then less is available for other environmental services that have a positive social value. Diverting river water for irrigation has a social cost only if downstream uses of that water would be negatively affected – if it means less water or water of poorer quality is available for other economically valuable activities like drinking, fishing, recreation, and hydropower. If water is sufficiently plentiful that these other uses are not significantly affected, then its opportunity cost for agricultural diversion would be close to zero.

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[6] This is directly analogous to the treatment of capital inputs in the estimation of TFP, where the value of capital services and not the value of capital stock is included in the measure of inputs (see section II).

Units of ecosystem services should be counted in such a way that they can be distinguished spatially and temporally. The value of ecosystem services is often highly dependent on the location and timing of the service. Their value also depends on the availability of substitutes or complementary goods and services. The value of improving the quality of a particular river for fishing and recreation will likely be higher near populated areas and where fewer alternative recreational spots exist. If natural resources are being overexploited to the detriment of future welfare, then it should be made visible today in national welfare and economic growth accounts.

A full treatment of the social cost of environmental services should consider not only its use value but also its existence value. A unique species of fish in a far-off river that people rarely visit may still be worth preserving (its existence value), and many in society are willing to pay to conserve environmental resources even if they never directly use them. Existence values for biodiversity may be particularly important. Even in an ecosystem where many species appear to provide redundant functions, these species may reveal unique and value traits as climate changes or new agricultural pests and diseases evolve. Preserving biodiversity retains the option to use them in the future when they may become important for agricultural, pharmaceutical, ecological or industrial applications. Thus, existence and option values are likely to be an important consideration in determining the social value of biodiversity stock and services (Day-Rubenstein et al. 2005).

2. Material inputs and mass balances

Conceptual approaches for incorporating ecological services into agricultural productivity accounting frameworks have focused on measuring and valuing the environmental cost or benefit of unintended by-products from agricultural production (the environmental sink functions in Figure 1.1). These unintended by-products (GHG emissions, nutrient and sediment loadings to water bodies, scenic value of farm landscapes, etc.) may be treated either as an output (where an undesirable output would have a negative price and thus reduce the aggregate value of output) or as though it were an input and thus part of total cost. It is also possible for an unintended by-product to be a positive environmental service, like carbon sequestration in soil, in which case it would have a positive price an increase the aggregate value of output.

Undesirable by-products from agricultural production typically arise as residuals from the use of material inputs, such as fertilizers, pesticides, animal feed and energy. Not all of the materials applied are used up in the production process and some are returned to the environment. Mass balance equations – where the residual is the difference between the amount of an input applied and the amount used up or absorbed in the harvest – provide an estimate of this residual. Mass balances estimate the potential, rather than actual, amount of pollutants. Non-material inputs like labor and capital do not produce undesirable by-products; they are used to increase output but also can be used to reduce residuals from material inputs. For example, through more careful placement of fertilizers, a higher proportion of the nutrients applied can be made available for crop growth leaving fewer nutrients as a residual. Still other inputs, like water filtration and treatment, may be purely for removing residuals from the environment. Efforts to reduce undesirable by-products from reaching the environment are referred to as abatement. Environmental and safety regulations governing the characteristics and use of material inputs are also part of abatement. These may impose costs on producers (including by raising the price of material inputs, either directly through taxes or indirectly through regulations that require these inputs to meet specific technical criteria) in order to keep harmful residuals from reaching the environment.

3. Valuing environmental services from agriculture

Among the key challenges of including environmental concerns in productivity metrics is valuing environmental services in a way that is comparable to market goods and services. Natural resources which have well-defined property rights, such as land, will have market prices that reflect at least some environmental services, like soil fertility. But other environmental services provided by the resource, such as soil carbon sequestration, may not be. In some cases, policies may create markets for environmental services (water markets and cap-and-trade systems for GHG, for example) and their prices can be observed. In most cases, however, prices are not observed for environmental services and alternative approaches are needed for valuation.

One method that has been proposed for valuing environmental services is its "shadow price." The shadow price (also called abatement cost) is the net cost to the producer of reducing an undesirable by-product of production by one unit. For example, reducing GHG emissions might mean fewer livestock are produced or fertilizers applied, and the shadow price of GHG emissions would be the foregone income when GHG emissions are reduced by one unit in the least costly way. Built-in to shadow prices are the effects of government regulations or other restrictions on farming practices. Regulations on the characteristics of allowable pesticides and how they are used can raise the cost of pesticide use to farmers, and thus the shadow price of pesticide residuals. Rules governing the allocation of scarce water for irrigation create shadow prices for water even if farmers do not pay for water explicitly. If the use of an environmental service is entirely unrestricted, its shadow price can be close to zero. Shadow prices will also be affected by how easily farmers can increase efficiency of input use (leaving fewer residuals) or find substitutes for them (Chambers 2015).

Shadow prices may under-value environmental services because they may not take into account alternative uses of the service. An alternative measure is the "social opportunity cost" of an environmental service, i.e., its value in its best alternative use. If nutrient loadings from agriculture are interfering with downstream fishing and recreation, then the benefit to downstream users from reducing loadings would be its social opportunity cost. The social opportunity cost would also include existence values of natural resources and environmental services. Methods for determining social opportunity costs of environmental services include contingent valuation (asking consumers of alternative uses their willingness to pay for cleaner water, for example) and revealed valuation (determining how much consumers are paying to obtain access to cleaner water, such as by traveling to other locations or cleaning up the resource).

Shadow prices and social opportunity costs provide conceptually different valuations of environmental sources. Shadow prices value environmental services from the perspective of agricultural producers. The social opportunity cost provides a measure of the worth of an environmental service from the perspective of society at large. Shadow prices reflect the cost to the producer of reducing the use of the environmental service (e.g., the higher cost of pest control due to regulations on pesticide usage, or lost net production if fertilizer use is lowered or other practices adopted to reduce nutrient loadings to water bodies). Social opportunity cost include the value of the environmental service in alternative uses as well as “existence” values (the value placed on an environmental good even if it is not used). With well-defined property rights over natural assets or optimal environmental regulations, shadow prices may be similar to social opportunity costs. In the absence of those conditions, we might expect shadow prices to be less than social opportunity costs. Each valuation measure can provide insights into resource use. Estimating and using shadow prices to value environmental services from agriculture can reveal important information on how environmental policies are affecting resource decisions and the welfare of farmers. Using social opportunity costs provides a more complete accounting of the welfare implications of using resources in agriculture as opposed to other uses, including future consumption (Gollop and Swinand 2001; Brandt et al. 2014).

B. Availability of National Measures of Agri-Environmental Services

Government statistical agencies have invested considerable resources into assessing the status of and valuing natural assets and environmental services. The European Framework for Integrated Environmental and Economic Accounting for Forests (European Commission 1999) and the United Nations-sponsored Millennium Ecosystem Assessment (1985) are examples of international efforts to assess the status and value of natural resource capital and their environmental services.

International organizations such as the OECD and the United Nations have made attempts to compile data on or construct estimates of environmental serves from agriculture in a consistent fashion across countries and over time. These efforts remain far from complete, however. This section briefly describes the current status of agri-environmental indicators provided by the OECD and FAO, and the UN System of Environmental-Economic Accounts for Agriculture, Forestry and Fisheries (SEEA AFF).

1. The OECD agri-environmental indicators database

Since the early 1990s the OECD has worked to assemble a database on national-scale Agri-Environmental Indicators (AEI). For OECD member countries, comparable information are (partially) available for 18 main indicators (Table 3.1). The AEI database tracks changes in these indicators over time, with data on individual indicators starting from as early as 1990 (OECD 2013). Indicators cover both natural resource assets used in agricultural production (soil, water, and biodiversity) as well as by-products from material inputs (fertilizer, feed, pesticides, energy) that use environmental services (sink functions).

The OECD has used these data to build measures of partial productivity and environmental efficiency (the ratio of agricultural output to the agri-environmental indicator). This provides a means of assessing the resource intensity of agricultural production (GHG emissions per volume of agricultural output, for example). Generally, these measures show that resource intensity has declined over time: fewer natural assets or undesirable by-produced are used or produced for a given volume of output. However, due to the growth in total output, this does not necessarily reduce total consumption of environmental services by the agricultural sector (OECD 2014).

While the AEI database represents a significant step toward TRP, the indicators are largely proxy measures for natural assets and environmental services. Measuring actual stocks of natural resources and flow of these stocks to agriculture is especially difficult. Changes in soil quality, for example, are measured by the share of land classified as having moderate to severe water and wind erosion risk, rather than as actual amounts of soil lost to erosion or changes in the chemical and physical structures of soils.

Much less progress has been made in the valuation of natural assets and environmental services used in agriculture. So far, most empirical efforts to develop TRP have focused on one or two environmental resources, such as GHG emissions or chemical use (Gollop and Swinand 1998, Hoang 2015). This work has largely relied on shadow prices rather than social opportunity costs for valuing environmental services.

2. FAO agri-environmental indicators

While the OECD AEI database only covers OECD-member countries, the FAO has begun to include some AEI’s for both developed and developing countries. Fairly complete estimates of GHG emissions from agriculture have been estimated for most countries of the world on an annual basis beginning in 1961 and are available from FAOSTAT. Other agri-environmental indicators in FAOSTAT are primarily about the extent of use of specific farm practices thought to be related to residuals from material inputs, such as amounts of fertilizers and pesticides applied, land under conservation tillage or organic agriculture, and the number of livestock on farms. It also includes some measures of natural resource assets – national average carbon content of soils and total water withdrawals for irrigation –but usually for only one or a few points in time.

3. The UN system of environmental-economic accounts for agriculture, forestry and fisheries

The System of Environmental-Economic Accounts for Agriculture, Forestry and Fisheries SEEA AFF is a statistical framework for the organization of data that permits the description and analysis of the relationship between the environment and the economic activities of agriculture, forestry and fisheries. It is part of the SEEA Central Framework for environmental-economic accounts adopted as an international statistical standard by the UN Statistical Commission in 2012. Broadly speaking, the SEEA provides the framework to account for (a) physical flows of various natural inputs, products and residuals (e.g. water, energy, emissions, waste); (b) stocks and changes in stocks of individual environmental assets (e.g. timber resources, fish resources, water resources, soil resources, land); and (c) economic transactions that can be considered environmentally related (e.g. environmental taxes, subsidies and similar transfers, environmental protection expenditure, production of environmental goods and services). Information on each of these types of flows, assets and transactions is organized following standard national accounting principles and following the classifications and definitions used in the national accounts and economic statistics more generally. The SEEA itself is a satellite account of the System of National Accounts.

The SEEA and SEEA AFF are still at a conceptual stage. Ecosystem accounting has not been implemented on a large scale in any country so far, although pilot studies are underway in select locations (Obst 2015).

Table 3.1. Main agri-environmental indicators in the OECD AEI database

Theme	Indicator	Indicator Definition	Nature of the environmental good, service or natural asset
Soil	Soil erosion	Agricultural land affected by water and wind erosion, classified as having moderate to severe water and wind erosion risk	ural asset (soil fertility)
Water	Water resources	Agricultural freshwater withdrawals	ural asset (flow)
		Irrigated land area	
		Water applied per hectare of irrigated land	
	Water quality	Nitrate, phosphorus and pesticide pollution derived from agriculture in surface water, groundwater and marine waters.	ural asset
.Air & Climate	Ammonia	Agricultural ammonia emissions	esirable output
	Greenhouse Gases (GHG)	Gross total agricultural greenhouse gas emissions (methane and nitrous oxide, but excluding carbon dioxide from land management or land use change)	esirable output
	Methyl Bromide	Methyl bromide use, expressed in tons of ozone depleting substance equivalents	esirable output
. Biodiversity	Farmland birds	Populations of a selected group of breeding bird species that are dependent on agricultural land for nesting or breeding	ural asset
	Agricultural land cover	Agricultural land cover types – arable crops, permanent crops and pasture areas.	ural asset
Agricultural Outputs, Material Inputs, & Land	Production	Agricultural production volume of crop and livestock commodities	Economic outputs (food, feed, fiber & energy)
	Nutrients	Gross agricultural nitrogen and phosphorus balances	Input with joint undesirable output
	Pesticides	Pesticide use, in tons of active ingredients	Input with joint undesirable output
	Energy	Direct on-farm energy consumption	Input with joint undesirable output (GHG emissions)
		Biofuel production to produce bioethanol and biodiesel from agricultural feedstocks	
	Land	Agricultural land use area	ural asset
		Certified organic farming area	
		Transgenic crops area	

Source: OECD, 2013.

IV. Roadmap Toward Assessing Sustainable Intensification

This White Paper is concerned with developing metrics for sustainable agricultural intensification. The preceding discussions largely sidestep the issue of what is meant by the term "sustainable", and instead concentrate on incorporating some estimates of environmental subsidies and impacts into productivity measurements. Despite a long conceptual history, "sustainability" was crystallized in the Brundtland Report, "Our Common Future" in 1987 as "meeting the needs of the present without compromising the ability of future generations to meet their needs". This conceptually useful definition is operationally so imprecise it is difficult to apply in practice. To help, and to acknowledge some different elements of sustainability, the Agenda for Development of the United Nations (1997), articulated three dimensions – the economic, social, and ecological. Our focus here is on incorporating metrics of environmental sustainability into productivity measures. This follows an often implicit assumption that profitability is an outcome of efficient production, and therefore social sustainability will be correlated with productivity as measured by TFP. Clearly this assumption is questionable, but rather than address the social dimensions explicitly, many of the issues discussed below (the need for sustainability, how to assess it, at what scale, its context-dependency, and its relationship with resilience) are applicable to the social agenda as well as the economic one.

Clearly, TFP and TRP provide useful, quantifiable indicators of resource productivity and can be developed at the national scale in the near and intermediate term. However, the extent to which they truly will capture the costs and benefits of the relationship between agriculture and the environment, and thus provide metrics for environmentally sustainable intensification in agriculture, is uncertain. This is largely because our understanding of the basic science underlying agricultural sustainability is insufficient. This section lays out wider context of agriculture-environment interactions and highlights firstly, the importance of ensuring sustainability (in terms of incorporating the environment fully within productivity measures) in Section A, and secondly, the importance of resilience (in Section B). The importance of sustainability and resilience then begs a series of questions: how are they related (Section C), at what spatial scale should they be assessed, and whether it is also possible to assess environmental limits (Section D)? Collectively this sets a roadmap for developing indicators of sustainable and resilient intensification, sketched out in Figure 4.1.

A. Why Environmental Sustainability is Important

Agricultural output is an ecosystem, or environmental, service that arises from the land. Agriculture is supported by soil as a substrate for roots to anchor plants, and relies on complex interactions between organic matter, nutrients and water, which in turn may be facilitated by soil biodiversity (whether earthworms, small invertebrates, fungi or microbes). Agriculture also relies on equitable climate. It may be supported also by a range of other ecosystem services, such as pollination from insects, or from natural pest control from a range of predators, such as small wasps. An agricultural unit, such as a field or farm, is not isolated from the rest of the world, and so activities within the field can affect the wider world, via emission of greenhouse gases (including ammonia and methane), contributing to climate change and reducing air quality, run off from agricultural land taking with it synthetic inputs and soil particles and affecting water quality and aquatic biodiversity and so on. Thus the provisioning services from agriculture (for food, feed, fuel, fiber) are intimately related to other ecosystem services that have some greater or lesser societal value.

In analogy with finance, ecosystem services can be thought of to arise (“flow”) from natural resources (“natural capital”): the soil in a field is the natural capital and from it arises the services of soil fertility, carbon storage, water storage and purification and so on. Whilst not an exact analogy, this framing emphasizes that maintaining natural capital is important in maintaining the ecosystem services that arise from it.

A useful operational definition of sustainability is the maintenance of ecosystem services from agricultural land. Whilst previous sections discuss the potential for incorporating environmental information as inputs (or outputs) of an index of total- or multi-factor productivity (TRP), such innovations are only a partial approach to measuring sustainability. This is for two principle reasons. First, putting natural capital inputs into the productivity calculation informs the rate of spend of the capital, whereas to manage capital stocks information is needed on both the rate of spend and the size of the capital. Second, biophysical (including ecological) systems are highly non-linear, and the relationship between the amount of natural capital and ecosystem services flowing from it is far from certain.

Consider, for example, soil erosion. Soils are obviously essential for agriculture, and yet are prone to loss via wind and water. How much loss is sustainable? To what extent is the decline in soil function linear with soil volume, or is there a threshold beyond which decline in function accelerates, and if so, how much soil needs to be lost to cross this threshold? In the literature, there are different ways of estimating the sustainable rate of soil loss, called the tolerance, or T-value, but these are inconsistent, outdated and therefore the estimates uncertain (Li et al. 2009). One area of consensus is that a tolerance should be closely related to the rate of soil formation to maintain long-term functionality. Across Europe, soil formation rates probably range from ca. 0.3 to 1.4 t ha^{-1} yr^{-1} (Verheijen et al. 2009), and probably broadly similar elsewhere. Yet, as several studies concur, many agricultural soils are eroding at a net rate of ~20 tons ha^{-1} yr^{-1} (Foucher et al. 2015). What do these estimates imply for soil functionality in the medium to long term? The key point is there remains significant scientific uncertainty about how to measure soil tolerances and how to interpret soil loss rates with respect to agricultural productivity and sustainability.

Whilst there is uncertainty about what how to estimate and interpret soil tolerances, it is, at least, conceptually easy to imagine soil volume and quality as a measureable stock. It is much less easy to apply this concept to biodiversity and the ecosystem services it contributes to. The natural capital in this case would be population size and viability (or viability's inverse, extinction risk). Population viability is a complex function of population size and may depend on *inter alia* feeding and nesting habitat, the amount, quality and temporal variance of resources, as well as their spatial distribution, and also on patterns of immigration and emigration between areas. Population viability is not linearly related to any of these factors so knowing population size is X and declining at Y% does not necessarily indicate, other than qualitatively, whether there is a low or high risk of extinction.

In conclusion, whilst TFP can be modified to TRP to highlight the extent to which natural capital or ecosystem services may be inputs or outputs of agricultural productivity, it will not necessarily inform about the sustainability of agriculture, *sensu stricto*, as the exact relationship between inputs/outputs and sustainability is uncertain. Knowing the rate of subsidy to agriculture (loss of soil quantity or quality per year, or loss of biodiversity) is not that informative of when or how, if that rate continues, yields will decline.

B. Volatility and the Need for Resilience

There is considerable evidence that the climate is changing in terms of a gradual global warming. Weather patterns are also changing, specifically bringing more extreme weather, which is impacting upon agricultural productivity in a variety of ways (Challinor et al. 2014, Coumou and Rahmstorf 2012, Hawkins et al. 2013, Wheeler and von Braun 2013). In addition, a range of other factors can contribute to variability in input prices and their availability, including emerging pests and diseases, food prices, oil prices and geo-political issues. These factors imply that an increasingly important property of agricultural systems is their resilience. Resilient systems are ones that are stable: either they are robust to perturbations, they quickly return to a pre-perturbed functional state. Non-resilient systems are ones that, once perturbed, take some time, or even never, return to the pre-perturbed state.

From dynamic systems theory, a stable state can be thought of as a dip in a surface, and the current state of the system can be described by a ball. When the ball is in a dip, the system is relatively stable: a perturbation may roll the ball up the side of its dip, but it will return to the same place quickly. If there are multiple stable states, the lip between adjacent dips are systemic tipping points: a perturbation that is small will move the ball up the side of the dip but it will roll back; if the perturbation pushes the ball over the lip is will roll into the next cup, and it will undergo a critical transition between alternative stable states (Scheffer et al. 2012). The dips, or stable states, can be created by technology (e.g. farming management maintains a high yielding system against most climatic shocks and pests and diseases) or natural processes (without human intervention, ecological communities are typically robust).

An example of a tipping point between alternative stable states in agriculture occurred in the dustbowl in the mid-west. What was, for the time, apparently stable and productive agriculture was perturbed by drought. Failure of crops, and thus farm enterprises, left land bare leading to significant soil erosion (over 20m ha of land lost up to 10cm of soil) which intensified the drought through surface-climate feedbacks (Fraser 2013, Worster 2004, Cook and Miller 2009). Loss of functionality from erosion led to very long term impacts on productivity and land value (Hornbeck 2012).

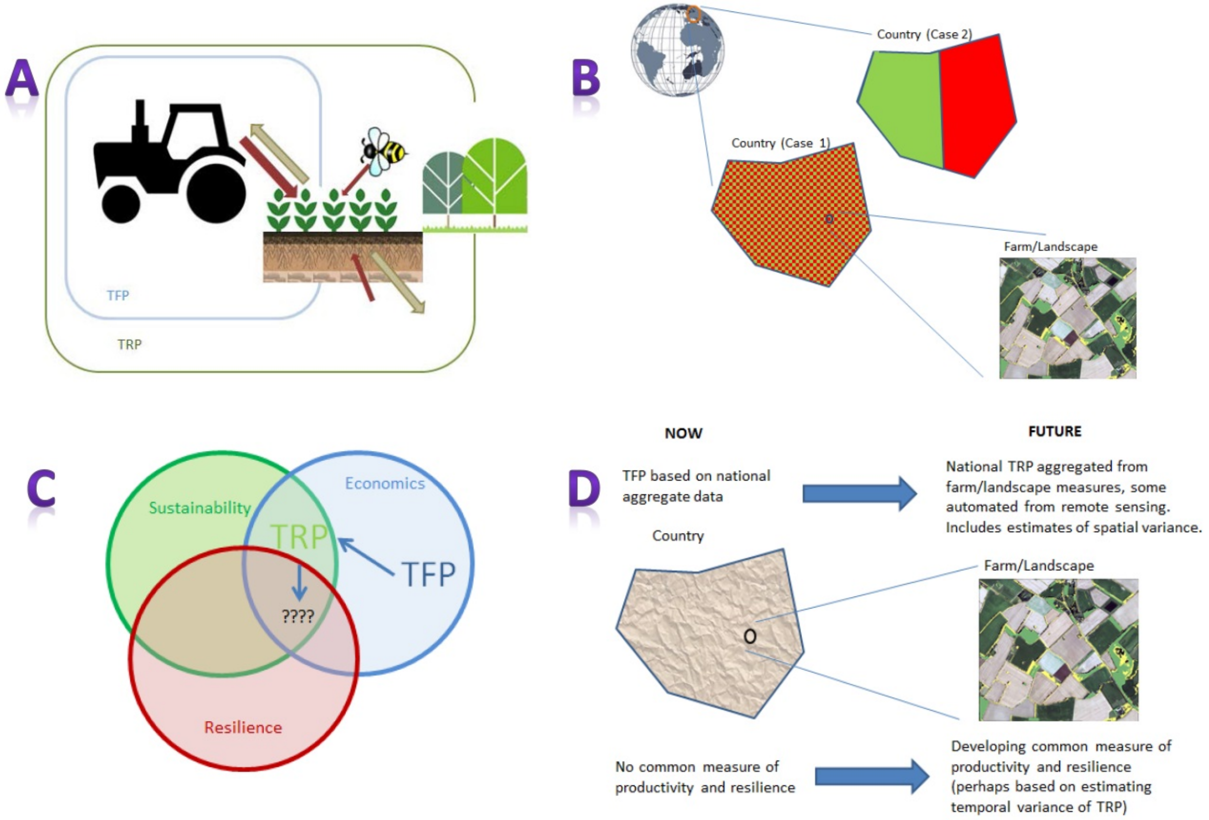
C. Will Sustainable Intensification Build Resilience?

To an extent, sustainability itself implies the system is robust to perturbations, in the sense that a robust system is resilient to change and will sustain its function over time. However this mapping is not necessarily exact. Resilience can imply redundancy in the system (in that a resilient supply chain may be one that normally over produces and wastes the excess, so called "insurance production", but that in the event of bad weather still has sufficient production). In this case, the inherent waste implies lower systemic sustainability, even if resilience is ensured. What has been sustainable and resilient in the past may not be in future as the environment – physical, political, economic - changes. Thus, if we are to ensure that agricultural production can be sustained into the future, resilience (response to perturbations) as well as sustainability (persistence of function into the future) are both important.

There is a school of thought that maximizing production efficiency via high inputs of capital, economies of scale, and large scale homogenous agriculture has been at the cost of resilience through concentrating risk in terms of "putting all of your eggs in one basket" (Abson et al. 2013). Bet-hedging, or diversification, is one strategy for gaining resilience, but one which may come at a cost to expected income. The extent to which resilience can be gained, like sustainability, without incurring production costs is an important research question.

Thus, the ideal performance criteria for agriculture would be those that metrics that assess whether agriculture is productive, sustainable and resilient (Fig 4.1c). Understanding resilience is difficult, because it necessarily needs an understanding of the closeness of thresholds, or tipping points. Whilst there are good examples of where tipping points have been crossed (in terms of the Dustbowl, or enrichment of water bodies) they remain largely theoretical rather than empirically understood.

Figure 4.1. Roadmap for developing Indicators of sustainable and resilient intensification



TFP based on national aggregate data

National TRP aggregated from farm/landscape measures, some automated from remote sensing. Includes estimates of spatial variance.

No common measure of productivity and resilience

Developing common measure of productivity and resilience (perhaps based on estimating temporal variance of TRP)

Note to Figure 4.1: TFP measures production efficiency in terms of marketized outputs per input (including fertilizer, capital and land), whereas in reality, outputs also arise from inputs of services from natural capital (e.g., pollination, aspects of soil "health" not captured in land value) and outputs also include impacts on e.g. water and air quality. TRP captures totality of inputs and outputs (A). However, national measures of TRP (or TFP) do not capture the spatial variability (B), such that the same national measure can arise from a mixture at different spatial scales, with implications for regional performance (the areas of red and green are the same in Country Case 1 and 2). In addition, TFP and TRP may estimate resource productivity (and thus "sustainability" in terms of natural capital) but they do not capture resilience, which in an increasingly variable world, is necessary (C). This provides the roadmap (D) to move from national estimates of TFP based on aggregate data, to local estimates of TRP (at farm and landscape level), which allows estimation of national average as well as spatial and temporal variance, the latter will relate to resilience. Increasingly, the burden of local data collection could be delivered through remote sensing.

D. Why are Performance Metrics for Sustainability and Resilience Problematic?

There are a number of reasons that building assessments of natural capital and ecosystem service flows into performance indicators for agriculture, to aid sustainable and resilient intensification, are problematic, some have been introduced in previous sections.

i. **Stocks and flows and limits.** The notion of natural capital and ecosystem flows is a natural one, and it is possible to measure both (though see 2 below). However, measuring, for example, the amount of soil does not necessarily measure the sustainability of current ecosystem services deriving from it as the stock-service-function relationship may be uncertain, non-linear and changing with time. Similarly, the biodiversity or abundance of pollinators does not necessarily inform the strength of pollination services (due to biological differences between species) (Fründ et al. 2013), although in general biodiversity may add resilience to functional relationships (Bartomeus et al. 2013, Brittain et al. 2013).

ii. **Scale and scale dependencies**. The scale at which ecosystem services are maintained, and the appropriate scale to assess agriculture's impacts varies between different ecosystem services. For example, viable populations of natural pest control insects or pollinators, are a property of a landscape, as this is the scale required to maintain populations of mobile organisms (Tscharntke et al. 2005), and there are non-linear relationships between what happens on a farm and how this would scale up to impacts at the landscape. Water quality is best measured at a catchment scale, as it is also the aggregate outcome of many farms. If a very large scale is assessed (e.g. national), there is the potential for the aggregate to mask significant regional variation and therefore not create a focus on regions or localities where unsustainable and unresilient agriculture is undertaken.

iii. **Context dependencies**. The impact of agriculture on the environment is rarely absolute, but context-dependent, such the same management can have different outcomes, or different management interventions can create similar outcomes. For example, an organic farm in a largely conventional landscape may have the same biodiversity as a conventional farm in a landscape where there are many organic farms (Gabriel et al. 2010). These context dependencies can arise from differences in a range of factors: climate, topography, soil type, surrounding landscape, local biodiversity as well as management and social factors. A pragmatic approach is to use, as a basic scale, the "landscape" (somewhat arbitrarily defined as a scale between farms and regions) and seek to maintain ecosystem services at this scale as this will reflect the majority of ecosystem services and also perhaps the way people interact with the rural environment.

iv. **Relationship between sustainability and resilience.** As discussed above, the relationship between yield, resilience and sustainability in aggregate is largely unknown. This is partly due to issues (1-3) above. It is also because the importance of resilience is itself coming into focus, as the speed with which the world is changing is becoming increasingly apparent. From a dynamic systems' perspective, there are some tools that can be adapted to indicate the trajectory towards a nearby critical transitions, such as the increasing amplitude of fluctuations in response to small perturbations, so called "flickering", but these are not universal near all tipping points (Scheffer et al. 2012). There is some indication from the literature that building resilience (e.g. by investment in improving soil quality) also improves sustainability. Nonetheless, conservation agriculture, often seen as iconic management for resilience as part of climate smart agriculture, brings with it a penalty in yields (Pittelkow et al. 2015). The relationship between resilience, sustainability and yields is therefore an open area of research.

v. **Lack of data.** The context and scale dependencies outlined above mean that small-scale studies, limited by place and study design, are difficult to interpret at larger scales. Using national farmland bird indices as proxies for "environmental health" at a national scale (see Chapter III) is rather more driven by pragmatism (in that those are the few data that are available in multiple countries) than scientific utility (partly because farmland specialists will respond in different ways depending on the local history of agriculture, and the evolutionary relationship between agriculture and birds in a country). However, the growth of remote sensing as a means of assessing ecosystem services (Ayanu et al. 2012, Cabello et al. 2012) and the development of citizen science applications for mobile phones[7] means obtaining data *de novo* may become increasingly feasible.

E. Designing the Ideal Indicator for Sustainable and Resilient Agricultural Productivity

Sustainability is about maintaining the integrity of function over the long-term, and given the inter-relationships between different ecosystem services important for society, agricultural productivity should not be at the expense of other ecosystem services, even if they currently have little marketable value[8]. Given that the world may face challenges of changing weather patterns, and the incidence of unprecedented conditions, it is important that agriculture retains resilience as well as sustainability. Human life depends on access to both food and water and so sustainability and resilience are, in the long term, as, or arguably more, important than productivity *per se*. Hence, developing metrics to assess productivity, sustainability and resilience are essential (Fig 4.1c).

A natural scale to conceptualize agricultural systems and their relationship to the environment is at the “landscape” scale, and maintaining an appropriate range of ecosystem services at this scale is a pragmatic definition of sustainability (Fig 4.1b). Thus, the ideal would be to seek, at this scale, multivariate descriptions of a “safe operating space” for agriculture. This safe operating space can be defined within sets of constraints on a range of biophysical and social indicators (e.g. biodiversity, soils, farm income, yields etc.), appropriate to the place.

Defining national measures of sustainable and resilient agriculture via scaling up from a smaller scale has the benefit of highlighting variance across space in performance, and therefore creating some focus on under- or over-performing region s and localities (Fig 4.1b). Starting from a national account, based on nationally available indicators of inputs and outputs, is a coarse measure that will not highlight, for example, regions where agriculture is under-performing or unsustainable, even if the aggregate account shows agriculture is competitive.

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[7] E.g. the British Geological Survey’s mySoil app.

[8] As mentioned in Article 1 of the Convention for Biological Diversity, biodiversity is valuable for intrinsic reasons as well as for utilitarian anthropocentric functions.

There are many arguments for not developing more ideal measures. These include the cost of data collection, the lack of historical records (and thus time series), and some significant unknowns (such as how to assess local constraints on ecosystem services and natural capital). Against this are the potential benefits of (a) substantially improved understanding of how to manage agriculture and other ecosystem services for the national benefit, and (b) understanding better when crossing local thresholds may erode function and therefore having an "early warning" indicator.

Significant advances are being made in utilizing remote sensing (airborne and satellite) for wide-area mapping of, for example, soil quality[9], soil moisture (Albergel et al. 2013), water quality (Olmanson et al. 2013), pests and diseases (Dong et al. 2012),non-cropped vegetation (Bradter et al. 2011) and biodiversity (Pettorelli et al. 2014). It is therefore feasible to imagine developing the specific tools, within a window of the next 3-5 years, to allow proxies of the important ecosystem services and natural capital stocks to be measured, simply and relatively cheaply, at a spatial (and temporal) scale that is properly informative to assessing sustainable and resilient agriculture. For example, a simple proxy for biodiversity is the amount, quality and connectivity of non-cropped land in agricultural landscapes, and it is already possible to map this remotely. Thus, as a first step, utilizing remote sensing to estimate natural capital stocks and ecosystem service flows, coupled with economic data from farms, would allow the estimation of TRP at a local scale and with some relatively low temporal frequency (i.e., biannually). Such a measure could provide estimates of spatial and temporal variability, the latter could be a proxy for resilience. This, then, is the immediate roadmap (Fig 4.1d).

Challenges remain, especially around assessing the non-linear relationship between natural capital and ecosystem services and developing indicators that allow thresholds to be identified before they are crossed (when recovering function may require transition back to a different state that may be costly or even impossible). In the longer term, it is possible to imagine utilizing placed-based data in a more sophisticated way. Using multi-scale modelling, and stochastic co-viability analysis, it is already possible to define the safe-operating space as the viability kernel that causes the system locally to sit within the constraint space. If there are

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[9] http://meetingorganizer.copernicus.org/EGU2013/EGU2013-2600.pdf

control parameters that are policy relevant, it is then possible to design policy – at an aggregate scale – that may bring this about. An important recent analysis of this type defined the set of viable public policies that met budgetary, farm-income and biodiversity constraints in France (Mouysset et al. 2014). Within this locally-defined but nationally aggregated safe operating space, maximizing agricultural productivity is desirable.

In sum, there is a necessity to develop metrics for sustainable and resilient agricultural production. An important property of these is spatial and temporal variance for assessing resilience and sustainability. This implies that national accounts are aggregated from smaller scales, and a “natural” scale is a “landscape” scale between farm and regional, as this reflects the scale of many ecosystem processes affected by agriculture. Remote sensing provides an opportunity to capture data efficiently (and to develop proxy measures) and there is significant benefit in utilizing this opportunity for developing indicators of sustainable agriculture and assess “safe operating spaces” where agriculture (for fuel, fiber, feed or food) can be maximized without impacting on other important sectors (such as water, recreation and amenity, etc.). The key research areas for developing useful measures are (a) indicators of ecosystem services and natural capital stocks developed from remote sensing, and (b) linking stocks to flows functionally in order to develop indicators of approaching thresholds or tipping points which may be crossed leading to the system tipping into an alternative stable state.

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Appendix: Notes on Agricultural Productivity Indices

A. Formulas for the Törnqvist and Fisher Productivity Indices

Productivity is defined as the ratio of two quantities (output over input). In a multi output-multi input economic setting, these quantities are the aggregate of other quantities (crops and animal commodities in the case of farm output; land, labor capital, and materials and services in the case of agricultural inputs). Market prices, which reflect the relative economic tradeoff between these goods, are used to put each quantity into a common unit of measurement in order to aggregate them into a composite good. The key to measuring productivity changes over time is to measure the rate of change in these quantities while accounting for their relative prices in market. For example, when comparing changes in aggregate quantity between two periods, the Laspeyres index uses the beginning period as the base year in which a set of fix prices are used, while the Paasche index uses the end period as the base year. However, since price changes elicit economic responses (for example, a rise in the price of labor induces producers to substitute capital for labor), holding prices fixed over long periods can give rise to the so-called "index number bias".

Divisia indices are a type of theoretical indices designed to incorporate continuous-time data on prices and quantities into productivity estimation in order to minimize this particular index number bias. The Fisher and Törnqvist indices are two discrete representations of Divisia indices that are widely used for productivity measurement (Jorgenson and Griliches, 1971). The Fisher index (Q_{0t}^{F}) is the geometric mean of Laspeyres and Paasche indices, defined as:

$$Q_{0t}^{F} = \sqrt{Q_{0t}^{L} Q_{0t}^{P}} \qquad \text{(A.1)}$$

where the Laspeyres index (Q_{0t}^{L}) is written as

$$Q_{0t}^{L} = \frac{\sum_{i=1}^{N} p_{i0} q_{it}}{\sum_{i=1}^{N} p_{i0} q_{i0}} = \sum_{i=1}^{N} W_{i0} \frac{q_{it}}{q_{i0}} \qquad \text{(A.2)}$$

and $W_{i0} = \frac{p_{i0} q_{i0}}{\sum_{i=1}^{N} p_{i0} q_{i0}}$ is the share of ith item in the total value of outputs or inputs in the base period (denoted by 0), while the Paasche index (Q_{0t}^{P}) is written as:

$$Q_{0t}^{P} = \frac{\sum_{i=1}^{N} p_{it}q_{it}}{\sum_{i=1}^{N} p_{it}q_{i0}} = \left\{\sum_{i=1}^{N} W_{it}\left(\frac{q_{i0}}{q_{it}}\right)\right\}^{-1} \tag{A.3}$$

and $W_{it} = \frac{p_{it}q_{it}}{\sum_{i=1}^{N} p_{it}q_{it}}$ is the share of ith item in the total value of outputs or inputs in the current period (denoted by t). In Equations (A.1) to (A.3), p_{i0} and p_{it} represent the prices of ith output or input items in the base and current periods and q_{i0} and q_{it} are the quantity of ith item in the two periods.

Given the same notations above, a Törnqvist index formula is defined as:

$$Q_{0t}^{T} = \prod_{i=1}^{N}\left(\frac{q_{it}}{q_{i0}}\right)^{\frac{1}{2}(W_{io}+W_{it})} \tag{A.4),}$$

which is the geometric mean of quantities between time 0 and t, using the revenue and cost shares as weights for outputs and inputs respectively. Note that to estimate the growth rate in index Q_{0t}^{T}, the Törnqvist index formula becomes:

$$G(Q_{0t}^{T}) = \sum_{i=1}^{N}\left(\frac{W_{io}+W_{it}}{2}\right)G\left(\frac{q_{it}}{q_{i0}}\right) \tag{A.5}$$

where $G(\circledast)$ indicates the growth rate of the quantity in parentheses. The growth rate in the aggregate quantity is simply the sum of the growth rates of the component quantities weighted by the mean value of their average revenue share (for output quantities) or average cost share (for input quantities).

B. Review of Agricultural TFP Estimates Across Countries

Since TFP is a key indicator of the economic competitiveness, measuring and comparing agricultural TFP among countries has been the subject of considerable study. A variety of methods and data have been employed to construct agricultural TFP for the G20 countries and the rest of the world, with more than 100 studies published since the early 1990s. Some of these studies used the “gold standard” approach, using detailed statistics on quantities and prices from national economic accounts to construct Fisher, Törnqvist, or other distance-function based TFP Indices. To make informative comparisons in the *TFP levels* among countries, differences in the purchasing power of national currencies (Capalbo and Antle 1988) as well as differences in the quality of natural resources (Ball et al. 2001) need to be taken into account. However, these issues are less important if only *TFP growth* rates are being compared.[10] Countries with sufficient information for the "gold standard" approach for agricultural TFP are mainly developed countries. Even for these cases, care must be taken to harmonize TFP growth accounting procedures in order to make productivity comparisons meaningful. For example, they need to employ similar methods for measuring agricultural capital stocks and the amount and quality of paid and unpaid labor employed on farms.

Due to the absence of detailed data on quantities and prices, others studies have used less rigorous but nonetheless informative methods to compare agricultural TFP among nations. These studies rely primarily on the Food and Agriculture Organization (FAO) statistics and cover a much broader set of countries, including developed and developing nations. A key limitation is the absence of complete, country-specific price information for agricultural outputs and inputs. To get around the lack of country-specific price data, these studies may use regional or international average prices (Fuglie 2015). Or, they may employ distance function methods to estimate a Malmquist Index.[11] A Malmquist Index can be estimated without price data using mathematical programming methods like Data Envelop Analysis (DES) or econometric methods like Stochastic Frontier Analysis (SFA) (Coelli and Rao 2005; Ludena et al. 2007; Nivievsky 2011).

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[10] Comparing TFP levels addresses the question: is country A more productive than country B? Comparing TFP growth only considers whether the productivity of country A is growing faster than the productivity of country B.

[11] The Malmquist index is defined in terms of distance functions. For comparing productivity among countries, a distance function indicates how far a country's current productivity is from a productivity frontier, where the frontier is defined by the most productive countries (Färe et al. 1994; Coelli and Rao 2005). The distance to the frontier indicates a country's relative efficiency. Over time, the frontier shifts out due to technical change. An improvement in TFP can come about by either an improvement in efficiency (moving closer to the frontier) or by technical change (a shift in the frontier). Empirically, a Malmquist index requires data on multiple countries to trace out the productivity frontier. Then other countries can be positioned according to their distance to the frontier (which, in an output-oriented Malmquist index, would be the increase in output possible using current inputs, based on what those on the productivity frontier have achieved). However, the definition of the productivity frontier depends on the set of countries included in the analysis. It also depends on how outputs and inputs are defined and measured. For example, if all classes of land and capital are aggregated together into "capital," a different productivity frontier will be mapped out than if more disaggregated categories of land and capital are included. Also, if differences in the quality of inputs and outputs are not accounted for, then these quality differences could be misinterpreted as technical inefficiency. For example, differences in the quality of agricultural land could account for much of the observed "distance" of a country to the productivity frontier, rather than inefficient use of currently available technology.

Table A1 lists a number of recent studies of agricultural TFP. These studies have used many different methods to construct production accounts and aggregate outputs and inputs into a productivity index. Most have been done to assess TFP growth in specific countries over time. For a few large countries like China, India and the United States, agricultural TFP has been estimated at both the national and state or provincial level. These country-specific studies generally draw upon data from national economic accounts, but their lack of harmonization in methods limits our ability to make comparisons between these countries. A few studies have attempted to compare agricultural productivity growth across multiple countries. The following provides a summary of studies that attempted to compare agricultural TFP growth across countries in a consistent way. Strengths and weaknesses of various methods and data sources are also described.

Ball et al. (1997b, 2001, 2010, 2015) and Sheng et al. (2013) attempt to provide harmonized cross-country agricultural TFP levels using national account data from the U.S. and other OECD countries. In our view, the methods developed in this body of work represents the best practice for data compilation and TFP estimation for cross-country comparison.

Table A1. Summary of literature on international comparisons of agricultural total factor productivity (TFP)

Category	Study	Period	Country coverage	Study Characteristics *
International TFP Comparisons with Harmonized Production Accounts				
	Ball et al (2015a)	1973-2011	USA, Canada, Australia, EU-14	Harmonized agricultural capital stocks and capital services
	Sheng et al (2013)	1961-2006	USA, Canada, Australia	TFP levels, Törnqvist/CCD index
	Ball et al (2010)	1973-2002	USA and EU-11	TFP levels, Törnqvist/CCD index
	Ball et al (2001)	1973-1993	USA and EU-9	TFP levels, Fisher/EKS index
International TFP Comparisons with FAO Data				
	Fuglie (2015)	1961-2012	World, regions, 172 countries	TFP growth accounting
	Fuglie (2012)	1961-2009	World, regions, 172 countries	TFP growth accounting
	Fuglie (2010a)	1961-2007	World, regions, 172 countries	TFP growth accounting
	Nivievsky (2011)	1975-2007	World & 13 regions	TFP growth accounting & Malmquist
	Ludena et al (2007)	1961-2001	116 countries	TFP growth, Malmquist (DEA)
	Headey et al (2010)	1970-2001	88 countries	TFP growth, Malmquist (DEA & SFA)
	Coelli & Rao (2005) ^	1980-2000	93 countries	TFP growth, Malmquist (DEA)
Country-Specific Agricultural TFP				
USA	Ball et al (2015b)	1948-2013	USA, national accounts	Gross output based, Törnqvist
	Andersen et al (2011)	1960-2002	USA, national & state	Gross output based, Törnqvist
	Ball et al (1999)	1960-1990	USA, national & state	Gross output based, Fisher
	Ball et al (1997a)	1948-1994	USA, national accounts	Gross output based, Fisher
	Ball (1985)	1948-1979	USA, national accounts	Gross output based, Törnqvist
Other countries	Saini & Lema (2015)	1913-2010	Argentina	Gross output based TFP, Törnqvist
	Bervejillo et al (2012)	1980-2010	Uruguay	Gross output based TFP, Törnqvist
	Liebenberg (2012)	1948-2010	South Africa	Gross output based TFP, Törnqvist
	Rada (2016)	1980-2008	India, national & state	Gross output based TFP, Törnqvist
	Cahill & Rich (2012)	1961-2006	Canada	Gross output based TFP, Törnqvist
	Suphannachart & Warr (2012)	1970-2006	Thailand	Value-added based, Törnqvist
	Rada & Buccola (2012)	1985, 1996, 2006	Brazil	TFP growth, Malmquist index (SFA)
	Swinnen et al (2012)	1989-2007	Transition economies	TFP growth, CD production function
	Fuglie (2010b)	1961-2006	Indonesia	Gross output based TFP, Törnqvist
	Hall & Scobie (2006)	1927-2006	New Zealand	Gross output based TFP, Törnqvist
	Thirtle et al (2008)	1953-2005	United Kingdom	Gross output based TFP, Törnqvist
	Matthews (2000)	1960-1998	Ireland	Gross output based TFP, Törnqvist
	Wang et al (2013)	1985-2007	China, national & provincial	Gross output based TFP, Törnqvist
	Fan & Zhang (2002)	1952-1997	China, national & provincial	Gross output based TFP, Törnqvist
	Kuroda (1997)	1960-1990	Japan	Gross output based TFP, Törnqvist
	Fernandez-Cornejo & Shumway (1997)	1960-1990	Mexico	Gross output based TFP, Törnqvist
	Lerman et al (2003)	1965-1990	USSR republics	TFP growth, CD production function

* Notes on study characteristics:
(i) Growth accounting uses cost shares and revenue shares as weights to determine average input and output growth rates, respectively.
(ii) Some studies have econometrically estimated a Cobb-Douglas (CD) production function to derive TFP using growth accounting, where the production elasticities are assumed to equal fixed cost shares for the purpose of input aggregation.
(iii) The Törnqvist/CCD index applies the Caves-Christensen-Diewert formula while the Fisher/EKS index applies the Elteto-Koves-Szulc formula to assure transitivity of bilateral Törnqvist indices when making multi-country comparisons.
(iv) The Malmquist Index, relying only on quantity data on inputs and outputs, has been estimated using Data Envelope Analysis (DEA) and Stochastic Frontier Analysis (SFA).

^ Coelli & Rao (2005) review earlier studies of multi-country agricultural TFP growth using the DEA-estimated Malmquist Index.

Following methods developed by Jorgenson and Nishimizu (1978), Ball et al. (2001) compared the levels of outputs, inputs and TFP between the US and nine EU countries (Belgium, Denmark, the Netherlands, France, Germany, the UK, Ireland, Italy and Greece) between 1973 and 1993. Using 1990 as the base year, they derived a Fisher bilateral output/input price index adjusted with the purchasing power parity measure (which is the international counterpart to the Fisher and Shell (1972) national output/input deflator), and then used the EKS formula (Elteto and Koves 1964, Szulc 1964) to achieve transitivity across countries.[12] Indirect quantity indices of outputs and inputs are estimated by dividing the total value by the corresponding price indices. This, for the first time, provided an international comparison of agricultural TFP levels and growth rates using accounting statistics.

Ball et al. (2010) extended this analysis to include two more EU countries (Spain and Sweden) and expanded the period of analysis through 2002. They derived a Törnqvist bilateral output/input price index and used the CCD formula (Caves, Christensen, and Diewert 1982b) to assure transitivity across countries. Implicit quantities of output and input were defined as the total value divided by their corresponding price, and the cross-country consistent agricultural TFP is derived as the implicit total output quantity divided by the implicit total input quantity. This study assessed how changes in productivity and exchange rates affected international competitiveness in agriculture between the US and the eleven EU countries (Belgium, the Netherlands, Denmark, France, Germany, the UK, Ireland, Italy, Greece, Spain, and Sweden) between 1973 and 2002.

Following this methodology, further collaborative work between the USDA's Economic Research Service, the Australian Bureau of Agricultural and Resource Economics and Sciences

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[12] Transitivity is a consistency property desirable in multilateral comparisons of outputs, inputs and productivity. Suppose we are comparing output among three countries, A, B, and C and a given point in time. A bilateral comparison of the output of A and B uses data on commodity production and prices from these two countries to aggregate output for each country and compare them. A common set of prices – based on some average of the prices of each commodity in each country, for example - is used to aggregate each country's output to see which produces more. Similarly, bilateral comparisons of output between A and C, and between B and C, are based on the quantities and prices of the two countries in the comparison. Let Y_{ij} be the ratio of output between countries i and j. Transitivity implies that $Y_{AC} = Y_{AB}/Y_{CB}$. However, the bilateral indices, which are constructed on the basis of the characteristics (i.e., price structure) of only two countries, do not necessarily have the transitivity property. Caves, Christensen and Diewert (1982b) provide a formula for adjusting bilateral Törnqvist indices so they will satisfy transitivity. Similarly, Elteto and Koves (1964) and Szulc (1964) give a formula for adjusting bilateral Fisher indices to make them transitive.

(ABARES), Agriculture and Ag-food Canada and Canada Statistics, and European institutions has been carried out. Sheng et al. (2013) compared agricultural TFP levels and growth between the US, Canada and Australia between 1961 and 2006 (findings from this study were presented at the 2014 G20 MACS in Brisbane). Work to extend this to include 17 OECD countries (the U.S., Canada, Australia, and 14 EU countries) is in process. One important component of this work, the measurement of land and capital stocks and services, has been completed (Ball et al. 2015). However, changes in data definitions and coverage in Eurostat since 2005 have slowed the effort to construct complete input and output measures for EU countries (Ball, personal communication).

In addition to the attempts made by Ball and his collaborators, there have been many other studies that have attempted to estimate and compare agricultural TFP estimates for a broader set of countries. These studies generally use data from the Food and Agriculture Organization (FAO) with either the growth accounting approach with conventional index formula (Fisher or Törnqvist indices) or the distance function approach (Malmquist indices). Due to data constraints on capital services, price information, and natural resource quality, these studies of using FAO data can only provide approximate estimates of agricultural TFP growth rates, and not TFP levels.

Fuglie (2010a, 2012, 2015) used a version of the growth accounting method applied to FAO data to compare agricultural TFP growth among 172 countries between 1961 and 2012. To obtain price weights for aggregating outputs, he used the FAO estimate of average global prices for agricultural commodities from 2004-2006. For input prices, he drew from country-level case studies, where available, to construct cost shares for major input categories like land, labor, capital and materials. Where unavailable, he used country-level evidence to construct regional average cost shares or econometrically estimated input elasticities for the cost shares. TFP indices were also constructed for global regions and the world average. Annual updates of these indices are available on the USDA's Economic Research Service's website (Fuglie and Rada 2015).

Other studies comparing multinational agricultural TFP growth have primarily relied upon distance function approaches like the Malmquist index, relying on quantity data alone.

Coelli and Rao (2005) used the FAO data to provide an estimate on agricultural TFP growth for 93 countries between 1980 and 2000. In this study, the Malmquist index method and the data envelopment analysis (DEA) technique were employed to address shortcomings of FAO data relating to price information.[13] This approach to productivity measure has sometimes given counter-intuitive results, such as technological regression (negative TFP growth) in many developing countries during the Green Revolution. Ludena et al. (2007) revised the Malmquist index method (following Nin-Pratt et al. 2003), in which technological regression is ruled out, to estimate agricultural TFP growth for 116 countries between 1961 and 2001. They also for disaggregated TFP growth for agriculture subsectors including crops, ruminants, and non-ruminant livestock, and developed projections for TFP growth in each subsector to 2040. Nonetheless, Malmquist productivity indices are also known to be sensitive to dimensionality, where results may change depending on the number of inputs and outputs and the set of countries included in the analysis.

Other recent studies focusing on estimates of cross-country agricultural TFP growth have sought to compare findings from estimation and investigate factors explaining differences in rates of TFP growth across countries. Headey et al. (2010) estimated Malmquist indices for 88 countries over the period of 1970–2001 using both DEA and SFA methods, and found the SFA estimates to be more plausible. Nivievsky (2011), which compared TFP growth patterns among 13 global regions using both “gold standard” and Malmquist indices. Depending on the method used, he found estimates of world agricultural annual TFP growth to vary from 1.9% to 2.6% between 1975 and 2007.

C. Accounting for the Environment in Productivity Indices: the SEEA Framework

A fundamental problem in environmental accounting is the valuation of natural resources. To measure productivity taking into account the resource depletion or service flows from natural resources, a valuation called a “user cost”, or “depletion rent”, of natural capital is needed in order to be consistent with the now standard methodology for constructing capital service aggregates (OECD 2001). In the context of accounting for the depletion of non-

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[13] This method is justifiable as the Malmquist index method allows the inputs and outputs to be aggregated through a distance function, which does not rely on explicit prices/value as weights.

renewable resources in a productivity analysis, Brandt, Schreyer and Zipperer (2016) have proposed using the unit resource rent as the user cost, allowing the use of World Bank (2011) estimates of the unit rent for various sub-soil assets in the construction of capital aggregates. Diewert and Fox (2015) compared this with a more standard user cost approach highlighted by Schreyer and Obst (2014), and pointed out some limitations of the unit rent method. There are, however, problems with implementing the standard approach in practice, and no study has yet implemented this approach for either non-renewables or ecosystem services.

A benefit of the traditional user cost approach is that it provides a decomposition into the sum of waiting services, rP^0S^0, revaluation, $-iP^0S^0$, and depletion terms, δP^1S^0, where P^t is the asset price for periods $t = 0,1$, S^0 is the period 0 asset stock, with an interest rate r, an asset-specific inflation rate i, and a resource depletion rate δ. This decomposition is useful in the environmental accounting context, where we want to measure net income. Three alternative income measures are given in Table A2.

Table A1: Alternative Income Concepts

Income Concept	Net Income Definition	User Cost Value
Gross Income (GDP)	Value Added	$(rP^0 - iP^0 + \delta P^1) S^0$
Income A	Value Added - δP^1S^0	$(rP^0 - iP^0) S^0$
Income B	Value Added - $\delta P^1S^0 + iP^0S^0$	$(rP^0) S^0$

Gross Income, or Gross Domestic Product (GDP) in the aggregate national context, is measured by Value Added. Income A results from the subtraction of the value of environmental depletion from Value Added to get a measure of net income. That is, income net of the value of natural resources exhausted in producing consumption goods; this accounts for the fact that national wealth has been diminished through economic activity impacting on environmental resources. Such an adjustment is consistent with the recommended approach of the SEEA.

An alternative is to also subtract the revaluation term from Value Added. This results in Income B in Table A2. This takes into account that a revaluation of the environmental resource can impact on wealth, due to e.g. increased information on resource degradation or exogenous shocks. This view is consistent with the real financial maintenance of capital concept advocated by Hayek (1941). Income A, in contrast, is consistent with the maintenance of physical capital concept of Pigou (1941).

In the usual case of a produced asset, the asset-specific inflation rate, i, will normally be negative due to, for example, foreseen obsolescence, so Gross Income > Income A > Income B. For a natural resource asset, scarcity and macroeconomic conditions driving international demand may cause i to be positive so that Income B may become larger than Gross Income. Alternatively, technological advances and degradation of the resource may cause i to fall in a similar manner to produced capital. Hayek (1941) argued that Income A would overstate the value of income in any period due to not accounting for (foreseen, produced-asset) obsolescence, and this argument appears to have merit in the natural resources context as well as the produced asset context.

Hence, valuation of natural resources has implications for assessing national economic wealth and economic growth, as well as productivity measurement.

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