A Manuel for Cross-country Comparison of Agricultural TFP for OECD Countries: Method and Data

Executive Summary

This manuscript aims at providing a standard method for constructing cross-country consistent production account for agriculture and measuring relative levels of agricultural TFP as well as its growth rates across countries for 17 out of 26 OECD countries for the period of 1973-2011. The construction of the database has allowed the dissemination of high quality statistics on growth and productivity using the methodologies of national accounts and input-output analysis. The database and the underlying production account will support empirical and theoretical research in the area of agricultural development and economic growth, such as study of the relationship between skill formation, input substitution, investment, technological progress and innovation on the one hand, and productivity, on the other.

1. Introduction

Given increasing food demand due to continuous population and economic growth, and the relatively fixed land area and reduced labor supply for agriculture, intensification of outputs (more yield or per capita) is a necessity for achieving the United Nation Sustainable Development Goal by 2030 (van der Brouer, 2020). In addition, agricultural output growth needs to be sustainable and resilient to external shocks, including resource degradation, climate change and the zoonotic/disease pandemic and so on. This sustainable intensification of agricultural output requires good metrics to manage. Agricultural Total Factor Productivity (TFP) are a widely applied measure of agricultural productivity levels and growth, gauging efficiency and efficacy of production units in farm sectors using multilateral inputs for gross outputs from an economic perspective. It also provides the best currently available means of assessing progress in sustainable agricultural intensification at the national or regional level, if properly adjusted to account for non-market inputs and outputs (i.e. bad output) (G20 MACs, 2015; OECD, 2021).

In literature, there are two broad quality tiers of currently available metrics of agricultural TFP – the first tier meets high international standards for economic productivity accounting like those recommend by the OECD or developed through the KLEMS model (used for developing internationally comparable TFP indexes of manufacturing sectors); the second tier provides less refined TFP indexes due to incomplete agricultural statistics. Presently the first tier is only separately available for a few countries, like, the United States, Canada and Australia, while the second tier is dominating in most other countries but distorting the public opinion of agricultural growth and cross-country disparity in reality (due to its systematic measurement errors) (OECD, XXXX; ERS, 2021). Therefore, it is essential for the academic and the government agencies to develop a standard approach and data compilation to construct up-to-date, accurate and internationally comparable TFP indexes for agriculture.

This manuscript aims at providing a standard method that could be used for measuring relative levels of agricultural TFP as well as rates of growth in agriculture for the OECD countries (as a start). To facilitate cross-country comparisons of TFP in agricultural sectors, we adopt the index number approach and base it on the growth accounting framework (Jorgenson, 1986). The approach is developed based on a strand of literature including but not restrict to Ball (1997), Ball et al. (2001, 2010), Sheng et al. (2015), Ball et al. (2008, 2018, 2020) and among others. We then apply the approach to construct the production account for agriculture consistently across 18 out of 26 OECD countries, including 14 EU countries (Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom) and the United States, Canada and Australia and measure and compare the relative levels of agricultural TFP for those countries for the period of 1973-2011.

This construction of the database on agricultural TFP for 17 OECD is aimed to support empirical and theoretical research in the area of agricultural development and economic growth, such as study of the relationship between skill formation, input substitution, investment, technological progress and innovation on the one hand, and productivity, on the other. The construction of the database has allowed the dissemination of high quality statistics on growth and productivity using the methodologies of national accounts and input-output analysis. A major advantage of growth accounts is that it is embedded in a clear analytical framework rooted in production functions and the theory of economic growth, and therefore allows the use of such output in additional analytical work (e.g. modeling, forecasting) and policy evaluation.

The rest of the manuscript is organized as below. Section 2 starts with providing a theoretical framework for conducting cross-country comparison of agricultural TFP using the production account data. Section 3 describes the detailed empirical method and procedure for compiling the production account for agriculture among the OECD countries, followed by a brief discussion on the data source in Section 4. Section 5 compares the related level of agricultural TFP for 18 OECD countries for the period of 1973-2011. Section 6 provides a roadmap for future extension of the current framework. Section makes conclusion.

2. Cross-country Agricultural TFP Comparison: A Theoretical Framework

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

$$TFP_t = \frac{Y_t}{X_t} \tag{1}$$

$$\frac{\Delta TFP_t}{TFP_t} = \frac{\Delta Y_t}{Y_t} - \frac{\Delta X_t}{X_t} \tag{2}$$

where TFP_t represents total factor productivity at time t, and Y_t, X_t and $\Delta Y_t, \Delta X_t$ are gross output and total inputs and their changes. Although both TFP level and growth are used to measure technological progress and efficiency improvement, TFP level is more difficult to calculate than TFP growth in making cross-country comparisons due to the heterogeneity of outputs produced and inputs used. To have meaningful comparisons of TFP levels, for example, requires that the quality of land, labor and other factors of production be measuring in a consistent fashion across space and over time.

Using Equations (1) and (2) to estimate agricultural TFP level and growth, one needs to aggregate various outputs and inputs in a consistent fashion. This is because, in agriculture, output is composed of multiple commodities produced by multiple inputs in a joint production process and the composition of outputs and inputs is changing over time. Under certain assumptions,[1] a general practice is to sum over output and input for each commodity for each country using the corresponding prices (or revenue/cost shares) as weights based on a pre-assumed index formula (Diewert 1992).[2] For cross-

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[1] These assumptions include 1) producers maximize profits and 2) there are free entry conditions in both product and factor markets.

[2] Please refer to Appendix I for detailed technical discussion.

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.

In practice, there are many pre-assumed index formulas that can be used for output and input aggregation, but the Törnqvist-Theil index can be considered the "gold standard" of TFP measurement. This is because, compared to other index formulas, the Törnqvist-Theil 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-Theil 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-Theil index formula performs better than other indexes for the construction of productivity indexes. As with the Fisher index, the Törnqvist-Theil index satisfies 21 reasonable tests — significantly more than any other index, when using the 'axiomatic test' approach (Fisher 1922). Third, the Törnqvist-Theil index provides a neat functional form for calculating TFP growth, which simplifies the estimation process and facilitates its cross-country and cross-region comparisons.[3]

To estimate agricultural TFP level and growth, both outputs and inputs must be defined and compiled in a consistent way. In conventional TFP estimates, the measure

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[3] In using the 'gold standard' approach, agricultural TFP growth equals the difference between the growth in aggregate output and the growth in aggregate input, with average revenue and cost shares over the period as corresponding weights (Ball et al. 1997).

is designed to reflect the efficiency of economic resources used for producing economic outputs and thus outputs and inputs are defined from an economic perspective. In agriculture, outputs used for TFP estimates refer to all goods and services that are produced by the industry, which are categorized into crops, livestock and livestock products and other outputs, while inputs used for TFP estimates include all economic resources available to farms, which are categorized into land, labor, capital and intermediate inputs. The following will discuss how the indirect approach is used to measure derive these aggregate input and output consistently comparable across countries.

Under competitive conditions, we can represent the production technology by a price or unit cost function that is dual to a linearly homogeneous production function for all twelve countries (Samuelson, 1953; Shephard, 1953, 1970):

$$\begin{aligned}\ln P = {} & \alpha_0 + \sum_i \alpha_i \ln W_i + \alpha_t T + \sum_d \alpha_d D_d + \frac{1}{2}\sum_i \sum_j \beta_{ij} \ln W_i \ln W_j + \sum_i \beta_{it} \ln W_i T \\ & + \sum_i \sum_d \beta_{id} \ln W_i D_d + \frac{1}{2}\beta_{tt} T^2 + \sum_d \beta_{td} T D_d + \frac{1}{2}\sum_d \beta_{dd} {D_d}^2, \qquad (3)\end{aligned}$$

where P is the price of the output in each country, W_i are input prices, T is time, D_d is a dummy variable equal to one for the corresponding country and zero otherwise, and d is an index of countries, running over Belgium, Denmark, Germany, Greece, Spain, France, Ireland, Italy, the Netherlands, Sweden, and the United Kingdom.[3] Since we express levels of output and input prices and levels of productivity relative to the United States, we omit a dummy variable for the United States from the price function. Since T and D_d interact with input prices, differences in levels of productivity across time and across countries are permitted to be non-neutral.

In examining the differences in production patterns among countries, we combine the price function with the demand functions for inputs. We can express these functions as equalities between the share of each input in the value of output and the elasticity of the output price with respect to the price of that input:[4]

$$v_{X_i} = \frac{\partial \ln P}{\partial \ln W_i} = \alpha_i + \sum_j \beta_{ij} \ln W_j + \beta_{it} T + \beta_{id} D_d . \tag{4}$$

The sum of the elasticities with respect to all inputs equals unity, so that the value shares also sum to unity.[5]

We can define the rate of productivity growth, say v_T, as the negative of the rate of growth of the output price with respect to time, holding input prices and the country dummy variables constant:

$$-v_T = \frac{\partial \ln P}{\partial T} = \alpha_t + \sum_i \beta_{it} \ln W_i + \beta_{tt} T + \beta_{td} D_d . \tag{5}$$

Similarly, we can define the difference in productivity between any country and the United States, say v_D, as the negative of the logarithmic derivative of the level of the output price with respect to the dummy variable representing differences in productivity between the countries, holding input prices and time constant:

$$-v_D = \frac{\partial \ln P}{\partial D_d} = \alpha_d + \beta_{id} \ln W_i + \beta_{td} T + \beta_{dd} D_d \,. \tag{6}$$

Our empirical application does not involve estimating the parameters of the price function; rather, we use index numbers that are exact for the translog specification. This approach was followed by Jorgenson and Nishimizu (1978, 1981) in their bilateral comparisons of output, input, and productivity for the United States and Japan. The average rate of productivity growth between two discrete points of time, say T and $T-1$, can be expressed as the difference between a weighted average of growth rates of input prices and the growth rates of the price of output for each country:

$$-\bar{v}_T = \ln P(T) - \ln P(T-1) - \sum_i \bar{v}_{X_i} [\ln W_i(T) - \ln W_i(T-1)], \tag{7}$$

where the average rate of technical change is

$$\bar{v}_T = \frac{1}{2}[v_T(T) + v_T(T-1)],$$

and the weights are given by the average value shares

$$\bar{v}_{X_i} = \frac{1}{2}[v_{X_i}(T) + v_{X_i}(T-1)].$$

The index number defined by (7) is the translog price index of productivity change suggested by Jorgenson and Griliches (1967).[6] Diewert (1976) showed that the index is exact for the translog price function.

The difference in productivity between any two countries, say $\hat{v}_D$, can be expressed as weighted averages of the differences between logarithms of the input prices for each country and the geometric mean of input prices over all twelve countries, less the difference between logarithms of the output price. Expressing differences in productivity relative to the United States:

$$-\hat{v}_D = \ln P(d) - \ln P(US) - \sum_i \hat{v}_{X_i}(d)[\ln W_i(d) - \overline{\ln W_i}] + \sum_i \hat{v}_{X_i}(US)[\ln W_i(US) - \overline{\ln W_i}], \tag{8}$$

where

$$\hat{v}_{X_i}(d) = \frac{1}{2}[v_{X_i}(d) + \frac{1}{N}\sum_d v_{X_i}(d)],$$

and a bar indicates the average over all N countries.

The translog index of productivity differences defined by (6) was introduced by Caves, Christensen, and Diewert (1982). Its use for making bilateral comparisons results in transitive multilateral comparisons that retain a high degree of characteristicity.[7]

To complete the methodology for comparing levels of output and input prices and levels of productivity among countries, we require specific forms for the functions defining the price of output and the prices of the inputs. We specify the price of output as a linearly homogeneous translog function of the prices of the components of output for all twelve countries:[8]

$$\ln P = \sum_i \alpha_i \ln P_i + \frac{1}{2}\sum_i \sum_j \beta_{ij} \ln P_i \ln P_j \ . \tag{9}$$

We can define the shares of these components in the value of total output by

$$v_{Y_i} = \frac{\partial \ln P}{\partial \ln P_i} = \alpha_i + \sum_j \beta_{ij} \ln P_j \ . \tag{10}$$

Since the price of output is a translog function of the prices of its components, the difference between successive logarithms of the price of output can be expressed as a weighted average of differences between logarithms of component prices with weights given by the average value shares:

$$\ln P(T) - \ln P(T-1) = \sum_i \bar{v}_{Y_i} [\ln P_i(T) - \ln P_i(T-1)], \tag{11}$$

Where

$$\bar{v}_{Y_i} = \frac{1}{2}[v_{Y_i}(T) + v_{Y_i}(T-1)].$$

Similarly, considering data for all twelve countries at a given point of time, the difference between logarithms of the price of output for any two countries can be expressed as weighted averages of the differences between logarithms of the component prices and the geometric average of component prices for the twelve countries. Expressing the differences in output prices relative to the United States:

$$\ln P(d) - \ln P(US) = \sum_i \hat{v}_{Y_i}(d)[\ln P_i(d) - \overline{\ln P_i}] - \sum_i \hat{v}_{Y_i}(US)[\ln P_i(US) - \overline{\ln P_i}] \tag{12}$$

Where

$$\hat{v}_{Y_i}(d) = \frac{1}{2}[v_{Y_i}(d) + \frac{1}{N}\sum_d v_{Y_i}(d)],$$

and

$$\overline{\ln P_i} = \frac{1}{N}\sum_d \ln P_i(d).$$

The price index in (12) represents the purchasing power parity between the currencies of the two countries expressed in terms of agricultural output.

If the input prices are translog functions of their components for all twelve countries we can express the differences between successive logarithms of input prices for a given country as:

$$\ln W_i(T) - \ln W_i(T-1) = \sum_j \bar{v}_{X_{ij}}[\ln W_{ij}(T) - \ln W_{ij}(T-1)], \qquad (13)$$

Where

$$\bar{v}_{X_{ij}} = \frac{1}{2}[v_{X_{ij}}(T) + v_{X_{ij}}(T-1)],$$

and $v_{X_{ij}}$ are the shares of the components in the value of the input aggregates.

Finally, we can express the differences between logarithms of input prices relative to the United States as:

$$\ln W_i(d) - \ln W_i(US) = \sum_j \hat{v}_{X_{ij}}(d)[\ln W_{ij}(d) - \overline{\ln W_{ij}}] - \sum_j \hat{v}_{X_{ij}}(US)[\ln W_{ij}(US) - \overline{\ln W_{ij}}]$$

(14)

where

$$\hat{v}_{X_{ij}}(d) = \frac{1}{2}[v_{X_{ij}}(d) + \frac{1}{N}\sum_d v_{X_{ij}}(d)]$$

and

$$\overline{\ln W_{ij}} = \frac{1}{N}\sum_d \ln W_{ij}(d).$$

The price indexes in (14) represent the purchasing power parities expressed in terms of the inputs employed in agriculture.

3. Constructing Production Account for Agriculture

We assume that data on production patterns in OECD countries are generated by a gross output model of production. Output is defined as gross production leaving the farm, as opposed to real value added. Inputs are not limited to land, labor and capital, but include intermediate inputs as well. The text in this section provides an overview of the data sources and methods used to construct the product and factor accounts for the period 1973-2011 for 18 out of 26 OECD countries.[9] A technical appendix providing a complete, detailed description of the data is available from the authors upon request.

3.1 Output and intermediate input.

Our measure of agricultural output includes deliveries to final demand and to intermediate demand in the non-farm sector. We also include deliveries to intermediate farm demand so long as these deliveries are intended for different production activities (*e.g.*, crop production intended for use in animal feeding).

One unconventional aspect of our measure of total output is the inclusion of output from "inseparable" secondary activities. These activities are defined as activities whose costs cannot be separately observed from those of the primary agricultural activity. Two types of secondary activities are distinguished. The first represents a continuation of the agricultural activity, such as the processing and packaging of agricultural products on the farm, while services relating to agricultural production, such as machine services for hire, are typical of the second.

The total output of the sector represents the sum of output of agricultural goods and the output of goods and services from secondary activities. We evaluate industry output from the point of view of the producer; that is, subsidies are added and indirect taxes are subtracted from market values.[10] In those countries where a forfeit system prevails, the difference between payments and refunds of the tax on value added (or VAT) is also included in the value of output.

Intermediate input consists of all goods and services consumed during the accounting period, excluding fixed capital. Those goods and services that are produced and consumed within the agricultural sector are included in intermediate input so long as they also enter the farm output accounts. The value of intermediate input includes taxes (other than the deductible VAT) less subsidies, whether paid to suppliers of intermediate goods or to agricultural producers.[11]

3.2 Capital input

The measurement of capital input begins with data on the stock of capital for each component of capital input, based on investments in constant prices.[12] At each point of time the stock the stock of capital, say $K(T)$, is the sum of past investments, say $I(T-\tau)$, weighted by the relative efficiencies of capital goods of each age τ, say $S(\tau)$:

$$K(T)=\sum_{\tau=0}^{\infty} S(\tau) I(T-\tau). \tag{15}$$

To estimate capital stock, we must introduce an explicit description of the decline in efficiency. This function, *S*, may be expressed in terms of two parameters, the service life of the asset L and a curvature or decay parameter β. One possible form of the efficiency function is given by:

$$\begin{aligned} S(\tau) &= (L-\tau)/(L-\beta\tau), \quad && (0 \leq \tau \leq L), \\ S(\tau) &= 0, && (\tau > L). \end{aligned} \tag{16}$$

This function is a form of a rectangular hyperbola that provides a general model incorporating several types of depreciation as special cases.

The value of β is restricted only to values less than or equal to one. For values of β greater than zero, the function S approaches zero at an increasing rate. For values less than zero, S approaches zero at a decreasing rate.

Little empirical evidence is available to suggest a precise value for β. However, two studies (Penson, Hughes, and Nelson, 1977; Romain, Penson, and Lambert, 1987) provide evidence that efficiency decay occurs more rapidly in the later years of service, corresponding to a value of β in the zero-one interval. For purposes of this study, it is assumed that the efficiency of a structure declines very slowly over most of its service life. The decay parameter for machinery and transportation equipment assumes that the decline in efficiency is more uniformly distributed over the asset's service life. Given these assumptions, the final β values chosen were 0.75 for structures and 0.5 for machinery and equipment.

The other variable in the efficiency function is the asset lifetime L. For each asset type, there exists some mean service life $\overline{L}$ around which there exists a distribution of actual service lives. In order to determine the amount of capital available for production, the actual service lives and the relative frequency of assets with these lives must be determined. It is assumed that this distribution may be accurately depicted by the normal distribution truncated at points two standard deviations before and after the mean service life.

Once the frequency of a true service life L is known, the decay function for that particular service life is calculated using the assumed value of β. This process is repeated for all other possible values of L. An aggregate efficiency function is then constructed as a weighted sum of individual efficiency functions using as weights the frequency of occurrence. This function not only reflects changes in efficiency, but also the discard distribution around the mean service life.

Firms undertaking investment decisions should add to capital stock if the present value of the net revenue generated by an additional unit of capital exceeds the purchase price of the asset. Stated algebraically, this condition is:

$$\sum_{t=1}^{\infty}\left(P\frac{\partial Y}{\partial K} - W_K \frac{\partial R_t}{\partial K} \right)(1+r)^{-t} > W_K, \tag{17}$$

where P is the price of output, W_K is the price paid for a new unit of capital, R_t is replacement investment, and r is the real discount rate.

To maximize net worth, firms will add to capital stock until (17) holds as an equality:

$$P\frac{\partial Y}{\partial K} = r W_K + r\sum_{t=1}^{\infty} W_K \frac{\partial R_t}{\partial K}(1+r)^{-t} = c, \tag{18}$$

where c is the implicit rental price of capital.

The rental price consists of two components. The first term, rW_K, represents the opportunity cost associated with the initial investment. The second term, $r\sum_{t=1}^{\infty} W_K \frac{\partial R_t}{\partial K}(1+r)^{-t}$, is the present value of the cost of all future replacements required to maintain the productive capacity of the capital stock.

We can simplify the expression for the rental price in the following way. Let F denote the present value of the stream of capacity depreciation on one unit of capital according to the mortality distribution m:

$$F = \sum_{\tau=1}^{\infty} m(\tau)\,(1+r)^{-\tau}, \tag{19}$$

where $m(\tau) = -[S(\tau) - S(\tau-1)],\ (\tau = 1,2,\ldots,L)$. It can be shown that

$$\sum_{t=1}^{\infty} \frac{\partial R_t}{\partial K}(1+r)^{-t} = \sum_{t=1}^{\infty} F^t = \frac{F}{(1-F)}, \tag{20}$$

so that

$$c = \frac{r\,W_K}{(1-F)}.^{13} \tag{21}$$

The real rate of return r in expression (19) is calculated as the nominal yield on government bonds less the rate of inflation as measured by the implicit deflator for gross domestic product.[14] An *ex ante* rate is obtained by expressing observed real rates as an ARIMA process.[15] We then calculate F holding the required real rate of return constant for that vintage of capital goods. In this way, implicit rental prices c are calculated for each asset type.

Although we estimate the decline in efficiency of capital goods for each component of capital input separately for all twelve countries, we assume that the relative efficiency of new capital goods is the same in each country. The appropriate purchasing power parity for new capital goods is the purchasing power parity for the corresponding component of investment goods output (OECD, p. 162). To obtain the purchasing power parity for capital input, we multiply the purchasing power parity for investment goods for any country by the ratio of the price of capital input in that country relative to the United States.

3.3 Land input

To estimate the stock of land in each country, we construct translog price indexes of land in farms. The stock of land is then constructed implicitly as the ratio of the value of land in farms to the translog price index. The rental price of land is obtained using (19), assuming zero replacement.

Spatial differences in land characteristics or quality prevent the direct comparison of observed prices. To account for these differences, indexes of relative prices of land are constructed using hedonic regression methods in which a good is viewed as a bundle of characteristics which contribute to the productivity derived from its use. According to the hedonic framework the price of a good represents the valuation of the characteristics “that are bundled in it”, and each characteristic is valued by its “implicit” price (Rosen, 1974). These prices are not observed directly and must be estimated from the hedonic price function.

A hedonic price function expresses the price of a good or service as a function of the quantities of the characteristics it embodies. Thus, the hedonic price function for land may be expressed as $W_L = W(X, D)$, where W_L represents the price of land, X is a vector of characteristics, and D is a vector of other variables.

The World Soil Resources Office of the U.S. Department of Agriculture's Natural Resource Conservation Service has compiled data on characteristics that capture differences in land quality.[16] These characteristics include soil acidity, salinity, and moisture stress, among others.

In areas with moisture stress, agriculture is not possible without irrigation. Hence irrigation (*i.e.*, the percentage of the cropland that is irrigated) is included as a separate variable. Because irrigation mitigates the negative impact of acidity on plant growth, the interaction between irrigation and soil acidity is included in the vector of characteristics.

In addition to environmental attributes, we also include a "population accessibility" score for each region in each country. These indexes are constructed using a gravity model of urban development, which provides a measure of accessibility to population concentrations (Shi, Phipps, and Colyer, 1997). A gravity index accounts for both population density and distance from that population. The index increases as population increases and/or distance from the population center decreases.

Other variables (denoted by D) are also included in the hedonic equation, and their selection depends not only on the underlying theory but also on the objectives of the study. If the main objective of the study is to obtain price indexes adjusted for quality, as in our case, the only variables that should be included in D are country dummy variables, which will capture all price effects other than quality. After allowing for differences in the levels of the characteristics, the part of the price difference not accounted for by the included characteristics will be reflected in the country dummy coefficients.

Finally, economic theory places few if any restrictions on the functional form of the hedonic price function. In this study, we adopt a generalized linear form, where the dependent variable and each of the continuous independent variables is represented by the Box-Cox transformation. This is a mathematical expression that assumes a different functional form depending on the transformation parameter, and which can assume both linear and logarithmic forms, as well as intermediate non-linear functional forms.

Thus the general functional form of our model is given by:

$$W_L(\lambda_0) = \sum_n \alpha_n X_n(\lambda_n) + \sum_d \gamma_d D_d + \varepsilon, \tag{22}$$

where $W_L(\lambda_0)$ is the Box-Cox transformation of the dependent price variable,

$W_L > 0$; that is,

$$W_L(\lambda_0) = \begin{cases} \dfrac{W_L^{\lambda_0} - 1}{\lambda_0}, \lambda_0 \neq 0, \\ \ln W_L, \lambda_0 = 0. \end{cases} \tag{23}$$

Similarly, $X_n(\lambda_n)$ is the Box-Cox transformation of the continuous quality variable X_n where $X_n(\lambda_n) = (X_n^{\lambda_n} - 1)/\lambda_n$ if $\lambda_n \neq 0$ and $X_n(\lambda_n) = \ln X_n$ if $\lambda_n = 0$. Variables represented by D are country dummy variables, not subject to transformation; λ, α, and γ are unknown parameter vectors, and ε is a stochastic disturbance.

3.3 Labor input

Data on labor input in agriculture consist of hours worked disaggregated by hired and self-employed and unpaid family workers (Eurostat). Compensation of hired farm workers is defined as the average hourly wage plus the value of perquisites and employer contributions to social insurance.

The compensation of self-employed workers is not directly observable. These data are derived using the accounting identity where the value of total product is equal to total factor outlay. Our index of labor input will then reflect differences in marginal products of hired and self-employed and unpaid family workers.

4. Data Source

In this section, we will discuss the data required to apply the proposed method to construct production account for agriculture in agriculture for the 17 OECD countries. Data in use are sourced from Australia, Canada, and the United States, and Euro Stat. A cross-country consistent production account was developed for agriculture and the same definition and method was used to derive each variable, although data were collected from different sources (a complete list of variables is provided in Appendix A). Most variables were collected for the period from 1973 to 2011, except for capital investment and asset prices, for which a longer time series was used.

4.1 Australia

Agricultural output quantity and value data were sourced primarily from the Australian Bureau of Agricultural Research Economics and Sciences' (ABARES) Agricultural Commodity Statistics. For some smaller commodity items price data were not available, and so an ABARES index of farm prices received was used instead.

Capital investment data were taken from the Australian Bureau of Statistics (ABS) National Accounts Database from 1960, and backcast to 1860 using data from Butlin (1977) and Powell (1974). Since no data are available for the deflator for transportation vehicles between 1920 and 1960, it is assumed to be the same as that for plant and machinery.

Data from the ABS Agricultural Census was used to estimate the land area used for agricultural production. Land prices were estimated using ABARES' Australian Agricultural and Grazing Industry Survey data after 1978 and backcast to 1960 using a

GDP deflator. For the base year (2005), more detailed data on land area and prices across 226 statistical local areas were collected for a hedonic regression analysis. Data on intermediate inputs (including total expenditure and price indexes) were sourced from ABARES' Agricultural Commodity Statistics.

The labour input quantity was estimated as the total number of hours worked each year, calculated by multiplying the number of workers by the average number of hours worked in a week, and the number of weeks worked each year. The average number of hours worked was obtained from the ABS Population Census and it is assumed there are 52 weeks of work each year.

4.2 Canada

Output quantity data were not directly available for Canada, but were estimated from total income from sales to processors, consumers, exporters and farm households (including within-sector use, waste, dockage, loss in handling and changes in closing stocks). Output price data were available from Statistics Canada CANSIM tables. Some non-separable forestry outputs were included in the aggregate output estimates.

A capital investment data series was compiled for the period 1926 to 2006. Data were not available for some early of this period, and so imputations were applied at the beginning of the investment series. Investment deflators (i.e. a price index) were constructed for the period 1926 to 1935 using import price data taken from CANSIM tables. For other years, disaggregated deflators for each asset grouping were taken directly from the national account statistics.

Land area data were sourced from the Canadian Agricultural Census, while land price data were obtained from the Canadian Agricultural Value-Added Account. All data series started from 1981, and were backcast using a fixed proportion of agricultural land in the total land, which was derived from the Census.

Data on intermediate input quantities and values were taken from the Statistics Canada publication Supply Disposition Balance Sheets, and other industry statistics. Individual price indexes were obtained from Statistics Canada or were imputed using a combination of prices. Finally, for inputs where data were unavailable, values were estimated to be 1 to 3 per cent of total costs and were added into the production account of agriculture.

The hired labour input was estimated using data from the Canadian Labour Force Survey and the Population Census of Canada. Estimates of the self-employed labour input (defined as the number of hours worked) were based on data from the Canadian Agricultural Census. The number of days worked were then converted into number of hours worked assuming 10 hours a day worked for 1961 to 1991, and using actual hours worked (obtained from the Canadian Labour Force Survey) for 1991 onwards. The input of unpaid family members was estimated as a proportion of the self-employed labour input.

4.3 United States

Agricultural output values were constructed by aggregating state-level data on farm cash receipts compiled by the United States Department of Agriculture Economic Research Service (USDA ERS). Price data were sourced from the USDA for most outputs and intermediate inputs.

Capital investment data were sourced from the Bureau of Economic Analysis, and deflators for transport vehicles were obtained from the Bureau of Labor Statistics. For non-dwelling buildings and structures, the implicit price deflator from the US National Accounts was used.

County-level land area data were collected from the US Census of Agriculture with interpolation between census years using spline functions and prices were obtained from the annual USDA survey on agricultural land values.

Intermediate input data were sourced from the USDA state farm income database. Price data were sourced from the National Accounts, the US Monthly Energy Review and the USDA agricultural prices database.

Labour input data for hired and self-employed workers were sourced from the US Census of Population and the US Current Population Survey.

4.4 European Countries

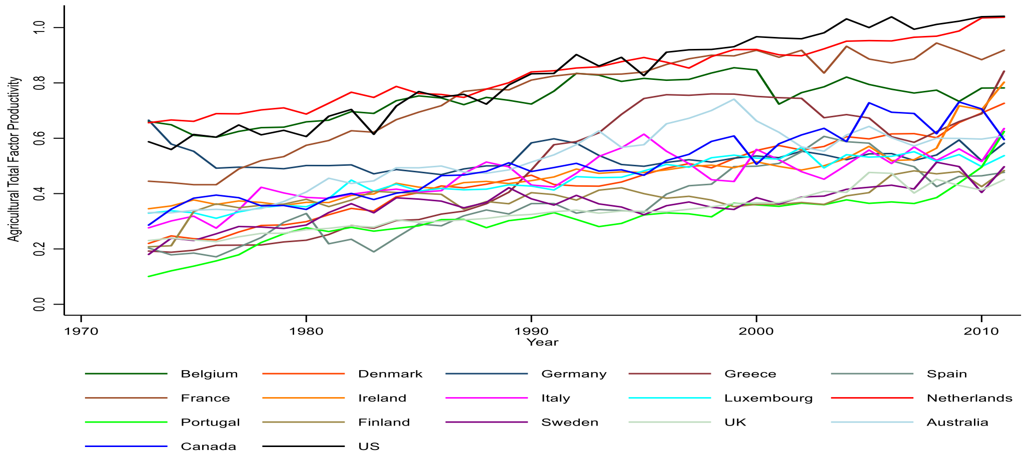
XXXXXXXXXXX (to be developed)

5. Comparing the Relative Levels of Agricultural TFP across 17 OECD Countries

Agricultural total factor productivity (TFP) in OECD countries has exhibited a relatively high growth rate over the past four decades, contributing to agricultural development throughout the world. Figure 1 shows the relative levels of agricultural TFP for 17 OECD countries over the 1973-2011 period. Over this period, agricultural TFP for the 17 OECD countries has grown at an average rate of 2 percent a year, which is about twice the global average for agriculture for the same time period and comparable to manufacturing and service sectors in the same OECD countries (FAO, 2018). Agricultural TFP levels in OECD countries are relatively higher than those in their developing country counterparts. The diffusion of technical knowledge promotes productivity growth in many developing countries (IFAD, 2015; Pardey and Alston, 2021).

Despite the rapid growth in the average rate of agricultural TFP, significant disparities remain in the rates of growth across countries. This contributes to differences in relative levels of TFP across countries (Figure 1a). As is shown in Figure 1b, the cross-sectional coefficient of variation of agricultural TFP declines rapidly in the 1970s, but held constant in the 1980s and the 1990s. The variance declined again in the 2000s, but at a decreasing rate. This suggests that cross-country differences in agricultural TFP levels remained large since the early 1980s. This result is contrary to the intuition that globalization is making technological innovation more accessible to these OECD countries which are in similar economic development stages (Gardner, 1996) and suffer less from institutional barriers and market distortions relative to their developing country counterparts (Gollin, Lagakos and Waugh, 2014b). It is even more puzzling that the remaining large gap in relative agricultural TFP levels in recent years also coincides with slowdowns in growth of agricultural productivity (Ball, Schimmelpfennig and Wang, 2013; Alston, Anderson and Pardey, 2015).4

Figure 1. Comparing agricultural TFP levels across 17 OECD countries



(a) Relative agricultural TFP levels

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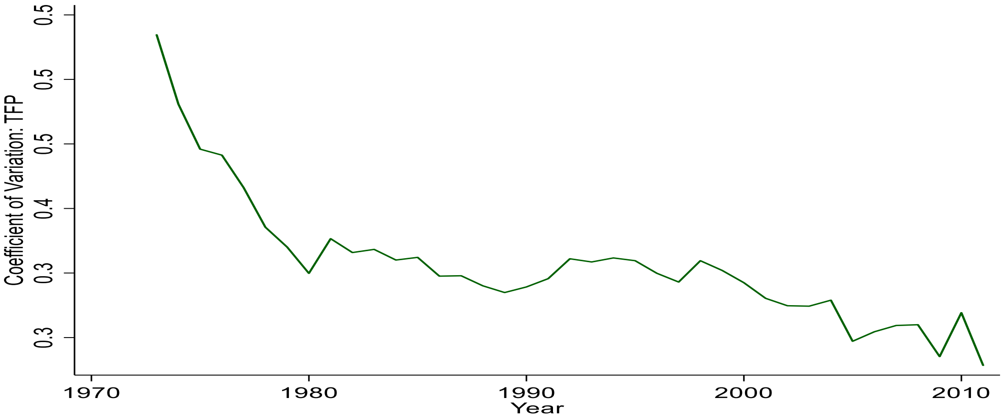
[4] A similar phenomenon is also observed by Ludina et al. (2007), Coelli and Rao (2005) and Fuglie and Rada (2018), although they have used different methodologies, data and indicators to measure agricultural productivity.



(b) Coefficient of variation of agricultural TFP across countries

Source: Authors' own estimates.

It is widely believed that agricultural technology is not readily transferrable across regions with different agro-ecological and climatic conditions. Thus, cross-country differences in agro-ecological and climatic conditions determine cross-country differences in agricultural productivity (McMillan and Rodrik, 2011; Gollin, Parente and Rogerson, 2014; Sheng, Ball and Nossal, 2015). However, the revolution in "biological", "mechanical", "chemical" and "information" technologies for the past three decades has facilitated technology transfer. For example, crop varieties and husbandry practices suitable for rainy regions were unsuitable for drought regions. Gene-modified or gene-editing technologies are changing the breeding technology, and drought-resistant crop varieties and husbandry practices are being created for drought regions. Meanwhile, tropical fruits can now be transplanted in nursery houses in most regions of the world. In both examples, capital accumulation plays an important role in supporting cross-country productivity growth.

For decades, many studies have examined the role of capital deepening in affecting productivity growth across countries but they do not agree that it will facilitate cross-country productivity convergence. For example, at the economy level, Baumol (1986), Barro and Sala-i-Martin (1995), Quah (1996, 1997) and Temple (1999) found that capital accumulation will foster the convergence of labor productivity across countries. But Kumar and Russell (2002), followed by Henderson and Russell (2005) and Badunenko, Henderson and Russell (2010), found that capital deepening can drive non-neutral technological progress and cause international productivity divergence. Applying the exercise to agriculture, Ball et al. (2001) examined the role of capital deepening in explaining cross-country agricultural productivity growth patterns in the US and 10 EU countries between 1973 and 1993. The results showed that capital deepening facilitated agricultural TFP convergence for the 11 OECD countries before the 1980s, providing support for the embodiment hypothesis (Jorgenson, 1966). However, they also showed that the role of capital deepening in facilitating agricultural TFP convergence across developed countries disappeared in the 1980s when net investment became negative.

After accounting for quality changes in capital and labor inputs,5 we show that relative

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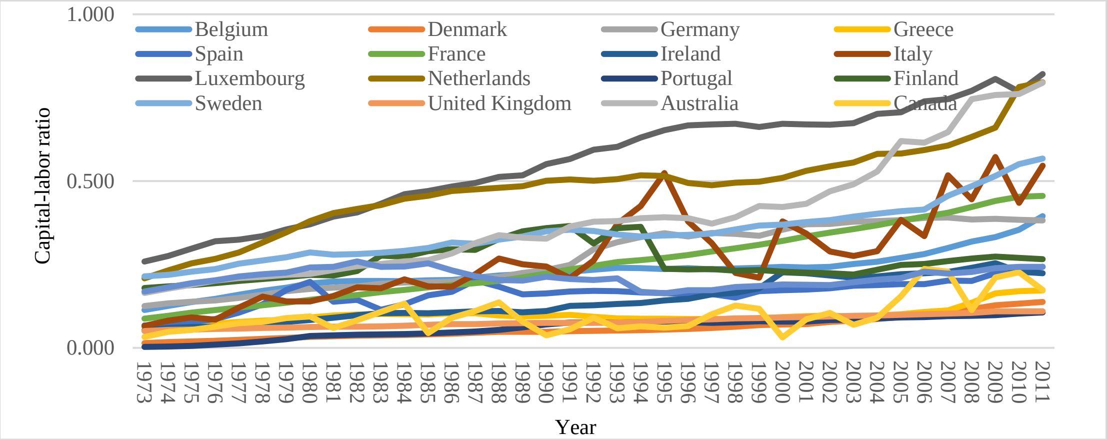
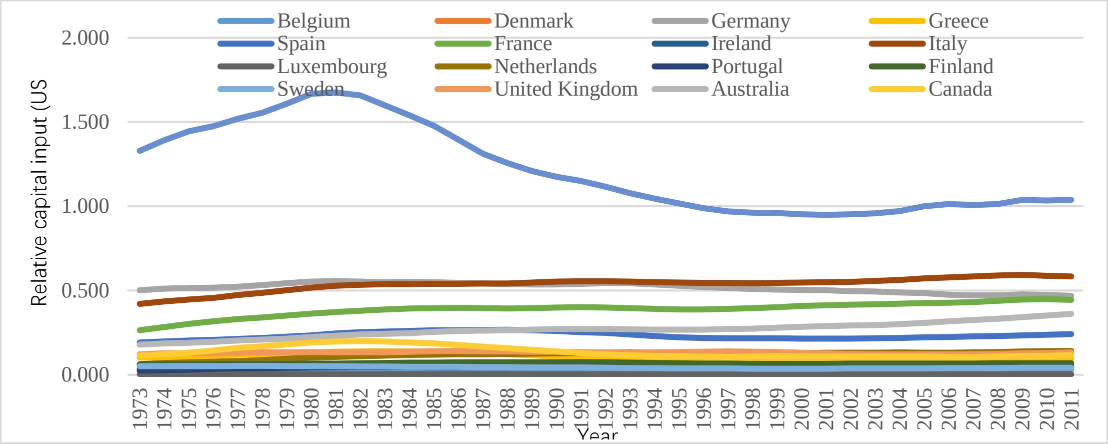
[5] Using a common methodology that allows comparisons across countries, Butzer, Mundlak and Larson (2010) compiled a data series on fixed capital in agriculture based on national accounts data. The fixed capital measure differs remarkably from the Food and Agriculture Organization's data on tractors, which has been widely used as a proxy for agricultural fixed capital. This highlights the importance of using accurate measures to better understand the cross-country differences in agricultural productivity (Gollin, Parente and Rogerson, 2004; Herrendorf and Schoellman, 2013; Gollin, Lagakos and Waugh, 2014a,b).

capital intensities for the 17 OECD countries and changes in agricultural TFP levels exhibit similar patterns. For example, as most OECD countries have faced increasing farm labor shortages since the 1970s, substitution of capital input for labor input closed the gap in cross-country capital intensities before the 1980s. However, capital intensities grew at a slower rate throughout the 1980s and the 1990s, when high real interest rates choked off new investment causing net obsolesce (Ball et al., 2001; Ball et al., 2010).This trend persisted through the 2000s. As seen in Figures 1 and 2, the relationship between convergence of capital intensities and convergence of cross-country agricultural TFP still requires a thorough empirical examination.

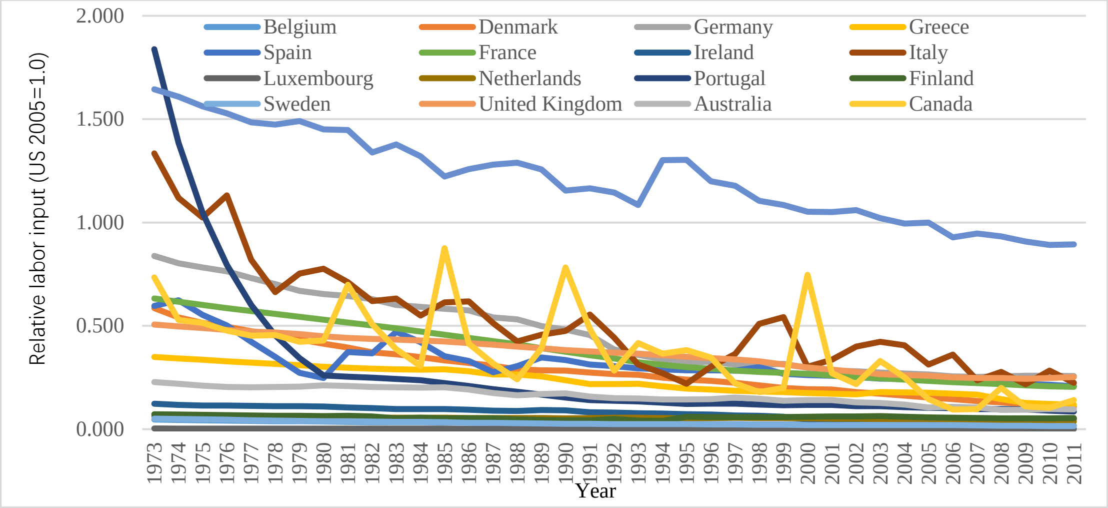
Figure 2. Comparing capital intensities, capital and labor input across 17 OECD countries: 1973-2011



Relative capital intensity levels



Relative capital input levels



(c) Relative labor input levels

Source: Authors' own estimates.

6. A Roadmap towards Next Stage: Some Issues in Debates

Although existing TFP measures provide useful information for analyzing technological progress and its impact on agricultural production across countries, several issues remain regarding methodology and data. These issues include (but are not restricted to) adjustment for input and output qualities, deriving the flow of capital services from productive capital stocks, and 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 accounting statistics could be combined with agro-ecological information to produce an environment adjusted TFP metric.

6.1 Adjustment for output and input quality

In reality, each output or input often includes multiple products of different qualities. A good productivity measure should reflect differences in the quality of outputs and inputs and their change over time. This is particularly important for dealing with the natural resource based inputs (for example, 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, for land used for similar purposes, 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 difference of these 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 progress.

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. Two approaches are available for quality adjustment, both requiring detailed information on quantities, quality attributes or prices of specific items to be considered for quality adjustment.

The first approach involves ‘direct’ adjustment of quantities. For example, the attributes of land such as soil quality may affect the quality of land service provided. An econometric technique (called the hedonic method) can be used to estimate the relative ‘importance’ of these attributes to land inputs. Then a quality-adjusted measure for land inputs can be calculated using the coefficients of the regression (as weights).

The second approach involves constructing a ‘quality-adjusted’ price index. This requires data on both prices and quantities of outputs and inputs according to quality. For example, a Törnqvist-Theil price index can be constructed for an output or input accounting for products of different qualities when appropriate weights are allocated. To the extent that prices are good indicators of quality, products of higher quality will be given greater weights and, as a result, they will have a greater influence on the resulting price index. As the price index is applied to measure the quantity of output or input, differences in quality will be captured by the aggregated quantity index.

Both approaches are widely used to adjust for quality disparities across regions and its change over time in land, labor, information and communication technology (ICT) products in productive capital (whose prices fall over time) and some intermediate inputs such as fertilizers and chemicals. In some cases, these approaches can also be used to account for the role of some non-economic inputs in affecting TFP estimates. For example, many studies have attempted to include rainfall and temperature (which are non-tradable) into land valuations and to measure their impact on agricultural TFP estimates adjusted for land quality.

6.2 Split between ‘flow’ and ‘stock’ variables

For productivity analysis, another challenging task is to derive a service ‘flow’ from their related ‘stock’ variables. A good example of this is to estimate capital services provided by the capital stock accumulated from past investments. For example, the flow of services from a tractor may be measured by the transportation of goods from one place to another and the accomplishment of other tasks (such as tillage and sowing) over a particular period. Since capital services (rather than capital stock) constitute the actual input in the production process (OECD 2001), they should be measured in physical units.

However, capital services are not 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 usually called the perpetual inventory method (PIM).

Although the concept of PIM is simple and clear, it is hard to estimate a measure of capital service. On the one hand, constructing productive capital stock is a very data-demanding exercise that typically requires long series of historical data on investment in specific types and vintages of capital goods over the entire service life of each type of asset. In most cases when data on historical investments are not available, market values of capital stocks or total assets are used as a substitute for productive capitals — the current inventory method (CIM) (OECD 2001). Compared with the PIM approach, the CIM approach is more widely used for international comparisons when the FAO data are used but its quality is in doubt due to lack of theoretical support. On the other hand, using different rates of return to investment to calculate capital services can lead to different estimates of TFP levels and growth. For example, both the 'ex post' and 'ex ante' methods are widely used to generate rates of return (Oulton 2005), but have never produced comparable results even for agricultural capital service in the US. The debate between Ball et al. (1997b) and Andersen et al. (2011) on the choice of ex ante versus ex post rates is ongoing and is primarily based on the assumptions regarding the depreciation function.

Applying a similar approach to analyze natural resource and environmental factors and their contribution to agricultural TFP estimates, some recent studies have attempted to construct the stock of cultivated biological resources (which include orchards, plantations, vineyards and breeding livestock) (similar to the treatment for productive capital stock) and derive their services as a proportion of biological resource stock (ABS 2014). Although the methodology has not been verified from a theoretical perspective, the logic can be further extended to account for other environment factors and their effects on agricultural TFP estimates.

6.3 Scale issue and consistency in aggregation

Scale- or context- issues, defined either from the spatial perspective or from the industry coverage perspective, are important in TFP estimation, and dominate in many facets of agricultural production and agro-ecological accountings. To reflect these issues in productivity measure, agricultural TFP levels and growth are often estimated at different aggregation levels (i.e. farm, region/industry or country) by using the 'gold standard' approach. In doing so, outputs and inputs (which are initially collected at the commodity or the farm levels) can always be re-organized and aggregated to any sub-categories for comparison, depending on data available. 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.

Where total output value equals total input value (as assumed in the accounting method), there is no profit at each aggregation level and there are no scale- or context- issues. However, agricultural production at a scale above the farm level and below the country level faces different market structures and operates under different environmental conditions, which generate economic profits or loss. This, in turn, undermines the assumption of constant returns to scale and there is always a gap between output and input values from year to year, especially at the scale below the country level (Balk 2007). To deal with this problem, Diewert and Morrison (1986) proposed using shift factors in the dual profit functions to account for positive or negative profits due to weather changes as well as for technological improvements. This helps to maintain efficiency of the accounting method in providing TFP measures at the disaggregated level but a question remains as to whether TFP estimates at different scales may be inconsistent with each other.

When extending the TFP estimation approach to cover environmental factors, scale issues become more problematic. In fact, many environmental factors are highly scale dependent, that is, looking at something at one scale may give a different impression from looking at it from another. A simple example might be: an agri-environmental measure, like a flower margin for pollinators, might be associated with many pollinators (and therefore looks good at the field scale), but the floral resources might simply be attracting bees from the wider landscape if the pollinator margin is in isolation, and therefore not contributing to wider habitat improvement necessary to improve population viability. More often, landscape- and neighbor-contexts mean that farm-level and landscape/catchment level outcomes are not well correlated.

Meanwhile, scale- and context-issues also affect farm business decision making when accounting for market/environmental factors. For example, with respect to organic farming in the UK, there is significant spatial aggregation of organic enterprises in the country (Gabriel et al 2009). Part of this is context (farmers in some geographies cannot compete on volume, so look for premium markets and produce lower volumes of higher value goods) and part scale (multiple organic farmers in an area are likely to stimulate a local market, which may be more difficult for individual farmers). All these complexities impose additional difficulties on the estimation of TFPenv.

7. Conclusions

XXXXXXXXXXXX (to be developed)

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Appendix A. Definition of Capital Input in Agriculture

Throughout the post-war period, there have been lively debates regarding the functioning of capital input in production and the process of capital formation in promoting economic growth and development (Hansen 1941; Henry 1942; Kuznets 1958). This is partly because growth in income per capita depends on technological progress as well as on the level of capital input per unit of labor, i.e., capital intensities (Griliches 1969; Jorgenson 1966).

For two reasons capital formation in agriculture is more important than in other sectors of the economy. First, agriculture is a risky business, because agricultural production usually involves the natural and biological activities beyond the control of human beings. To compete with other sectors in the economy, the industry needs to have a higher productivity as the risk premium. With the same trend in technological progress as in other sectors, agricultural production thus has to rely on using more working or operating capital than other sectors. Second, agriculture is usually located in sparsely populated remote rural areas where both public infrastructure and industrial-linkages are weaker. Therefore, using more capital equipment such as tractors and transportation vehicles in production will help workers in agriculture to work more independently and to overcome the lack of public infrastructure. Meanwhile, some studies also show that increasing capital equipment per unit of labor also helps to promote technology diffusion, which is usually embodied in capital investment (or the embodiment hypothesis) (Tweeten 1980; Acemoglu 2010).

In this section, we construct estimates of the capital stock and rental price for each asset type in each country. For depreciable assets, the perpetual inventory method is used to develop capital stocks from data on investment in constant prices. Data on investment for member states of the European Union are from Beutel (1997). More recently, these data are from the Economic Accounts of Agriculture (Eurostat). For Australia, data are from the Australian Bureau of Statistics. Statistics Canada provided data for Canada, while data for the United States were provided by the Economic Research Service of the US Department of Agriculture. Capital rental prices for each asset are based on the correspondence between the purchase price of the asset and the discounted value of future service flows from that asset.

In general, capital inputs in agricultural consist of three categories: services from land, depreciable capital assets and biological and inventory stock.[6] Among the three, depreciable capital is the most important one for agricultural production. It is the most frequently used capital input in daily production activities that could embody the newly invented technologies. Since depreciable capital input is mainly determined by farmers' investment behaviours in a competitive capital market, we can derive estimates of capital stocks from initial investments over time. The system of National Accounts

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[6] Land service is the most important capital input, without which most agricultural production activities could not take place. However, measuring land input is different from measuring other capital inputs as agricultural land has indestructible situation value. To measure land input in agricultural production may involve using not only some non-economic factors such as natural climate conditions, land slope and soil quality, but also the opportunity cost of land usage for non-agricultural activities, influenced by land market institutional arrangements and nearby economic development. This issue will be discussed in a separate chapter.

2008 (SNA 2008, p.204-206) provides the definition for three types of depreciable assets for agricultural production: non-dwelling building and structures, transportation equipment, and other machinery and equipment.

Non-dwelling buildings and structures includes whole buildings or parts of buildings not designated as dwellings. Fixtures, facilities and equipment that are integral parts of the structures are included. For new buildings, costs of site clearance and preparation are included. Public monuments identified primarily as non-residential buildings are also included.

Transportation equipment consists of equipment for moving people and objects. Examples include transport equipment such as motor vehicles, trailers and semi-trailers; ships; railway and tramway locomotives and rolling stock; aircraft and spacecraft; and motorcycles, bicycles etc.

Other machinery and equipment consists of machinery and equipment not elsewhere classified. Examples include categories of fixed capital formation for general purpose machinery (i.e. tractors and other power machines), special purpose machinery, electrical machinery and apparatus etc.

In many cases, tractors and other power machinery used for agricultural production are also separately treated (when the data are available), but they are combined in our study for consistent treatment across countries. The criteria used to categorize these capital inputs are different average service lives and different depreciation profiles. Yet, it is difficult to evaluate the relative importance of these three types of capital inputs in agriculture.

Although depreciable capital inputs in agriculture are well defined in concept, it is still a challenging task to measure it practically for two reasons. First, capital assets are purchased at one time period but they are used in many subsequent periods, which are difficult to measure. Assumptions on physical decay, obsolescence (including disposal), replacement and durability are required to derive the accumulation of capital as well as the flow of services from the stock. In this sense, using different assumptions may generate different estimates of capital inputs. Second, there is usually not a competitive market to reallocate capital services among farmers. In other words, the consumer of capital services is also often the supplier, such that the entire transaction occurs within the internal accounts of the economic unit making the investment decision, and so is unobservable by economists (Griliches and Jorgenson 1966; Andersen et al. 2011). Hence, little information is available on rental rates and the ex-post usage of capital assets for consistent cross-region and cross-country comparisons.

Not having access to long time-series data on investment and the price of depreciable assets in agriculture, researchers often use data on the number of tractors or total power of machinery as a proxy for fixed capital input in cross-country comparisons. For example, Mundlak et al. (1999) and Coelli and Rao (2005) summarise early studies of cross-country comparisons of agricultural productivity, including Bhattacharjee (1955), Hayami and Ruttan (1970, 1971), Evenson and Kislev (1975), Nguyen (1979), Mundlak and Hellinghausen (1982), Kawagoe and Hayami (1983, 1985), Antle (1983), and Lau and Yotopoulos (1989). In these studies, various measurements of capital inputs are used based on combinations of farm machinery, tractors, livestock, orchards, and, sometimes even data on irrigation and farm structures and so on. Other studies, though differing in methodology, use some form of livestock and machinery stock to measure capital inputs in agriculture. These studies include Fugginiti and Perrin (1993, 1998), Block (1994), Craig et al. (1997), Wiebe et al. (2003), Cermeno et al. (2003), Lio and Liu (2008) and Cermeno and Vazquez (2009).

The above studies provide no convincing proxies for real capital input in agriculture (Butzer et al. 2010). Neither do these measures allow for the estimation of agricultural production functions nor do they explain the cross-country disparities in agricultural productivity. To resolve the problem, recent studies attempt to use the perpetual inventory method (PIM) to estimate capital stock and capital services in agriculture using national accounts data for cross-country comparisons. As an example, Mundlak et al. (2008) and Butzer et al. (2010) used the national accounts statistics to construct a data series on aggregate depreciable capital, livestock and tree stocks in agriculture (from FAO) for 30 countries for the period 1970-2000. Alternatively, Ball et al. (2001, 2008, 2010) and Ball et al. (2016) use the national accounts statistics to measure real capital input of land and depreciable capital assets in the United States and 10 EU countries between 1973 and 2002 and in 17 OECD countries between 1973 and 2011 respectively. Both groups of studies show that as economies grow, agricultural capital stocks accumulate and the composition of agricultural capital inputs changes.

By summarizing the recent literature, this chapter will provide a general method that could be used to measure the relative levels of depreciable capital input for the OECD countries, and discusses a set of assumptions to be used. In particular, we will focus on relaxing the implicit assumption of fixed asset lives in the estimation of capital stock.

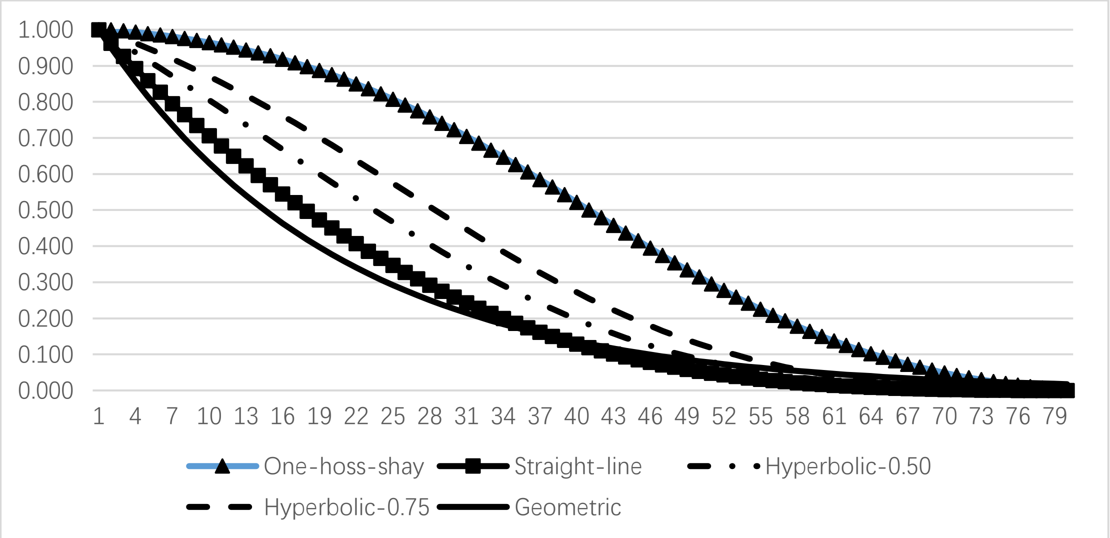
Appendix B. Comparing the impact of using alternative depreciation profile assumptions on capital stock and capital services.

In the literature, the estimated capital stock and capital services will differ substantially depending on with the choice of different depreciation profile. While there are four widely used depreciation profiles (including one-hoss-shay, hyperbolic depreciation, a constant rate geometric depreciation and a linear depreciation), many previous studies tend to use the constant rate geometric deprecation profile for efficiency and depreciation estimates due to its simplicity in application. However, using the geometric depreciation profile involves an implicit assumption that service lives and efficiency patterns of capital assets are known with certainty. This implicit assumption of fixed service life is unrealistic. In a world of uncertainty, some assets will be retired before the end of their average service lives (T) while others will be retired after (T).

To deal with this problem, we propose to use the hyperbolic depreciation profile, assuming variable service lives for each asset type. There are two reasons. First, this method provides a more general functional form to different types of capital depreciation profiles. In particular, when we choose different parameters, the hyperbolic depreciation profile can be used to approximate a variety of depreciation profiles. Second, the hyperbolic depreciation profile is compatible with the variable service life assumption. While clear in theory, there is no empirical evidence from the cross-country comparison perspective. This appendix examines whether there will be significant differences in capital stock and capital service estimates when one chooses between different depreciation profiles (geometric depreciation with fixed service life) vs. hyperbolic depreciation with variable service life) using the data for 17 OECD countries between 1973 and 2011. Three groups of results are discussed below.

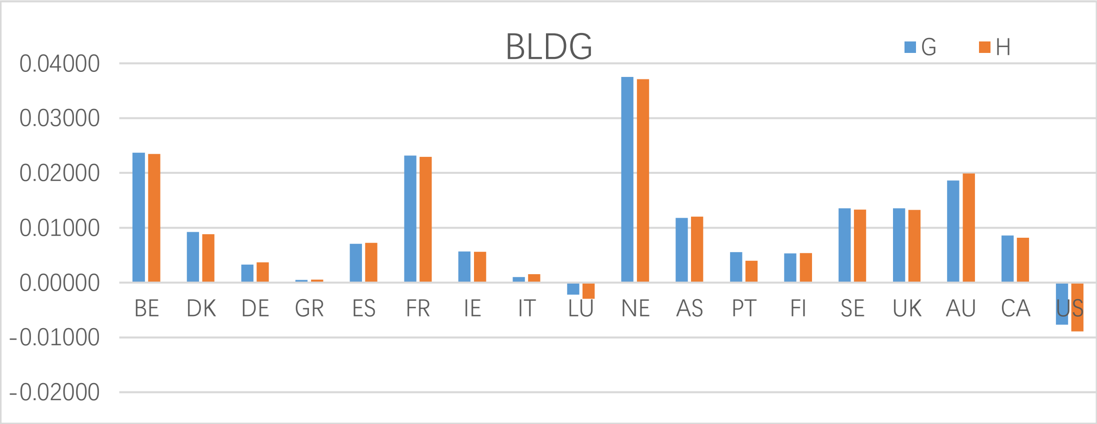
First, we compare the depreciation curves obtained from the geometric depreciation profile with fixed service life and from the hyperbolic depreciation profile with variable service life. The results show that the depreciation curves obtained from the two assumptions track well with each other, although capital asset seems to depreciate a bit more quickly under the assumption of a constant-rate geometric depreciation.

Figure B1. **Comparing depreciation curve from alternative assumptions**

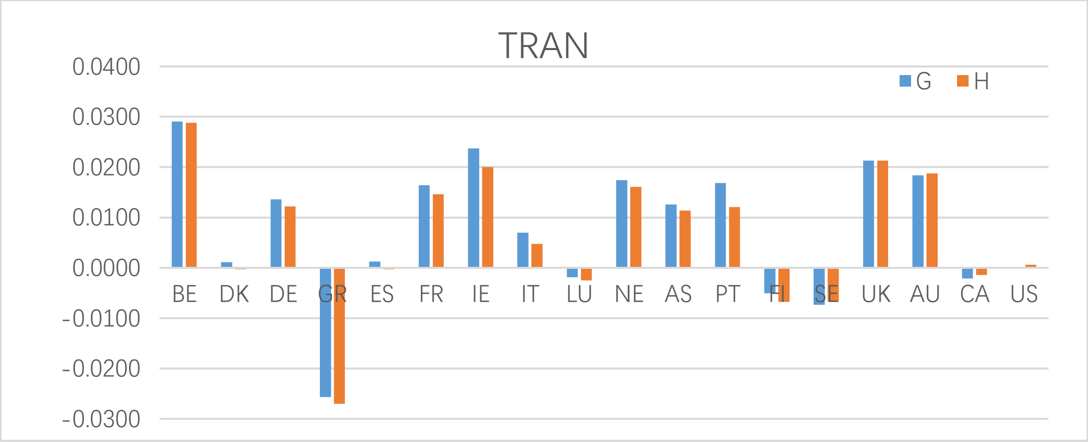


Second, we compare capital stock estimates obtained from the geometric depreciation profile with fixed service life and from the hyperbolic depreciation profile with variable service life. The results show that the estimated capital stock based on the hyperbolic depreciation assumption is much larger than that based on the geometric depreciation assumption (although the growth rates of capital stocks obtained from the two assumptions are almost identical? same). The differences in relative levels of capital stock estimates ranged from 90% to 99% depending on asset types and time.

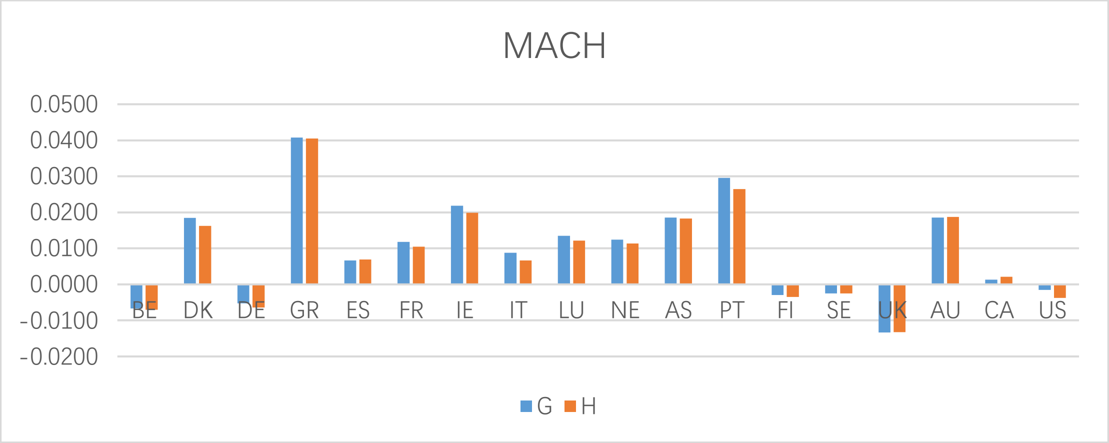
Figure B2. Comparing the growth rate of capital stock using alternative depreciation profiles



(a) Non-dwelling building and structure

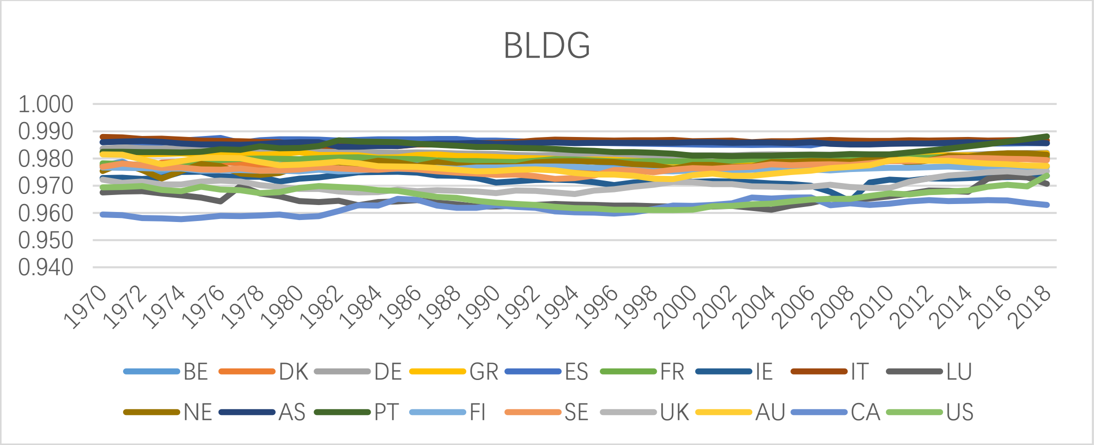


(b) Transportation vehicles

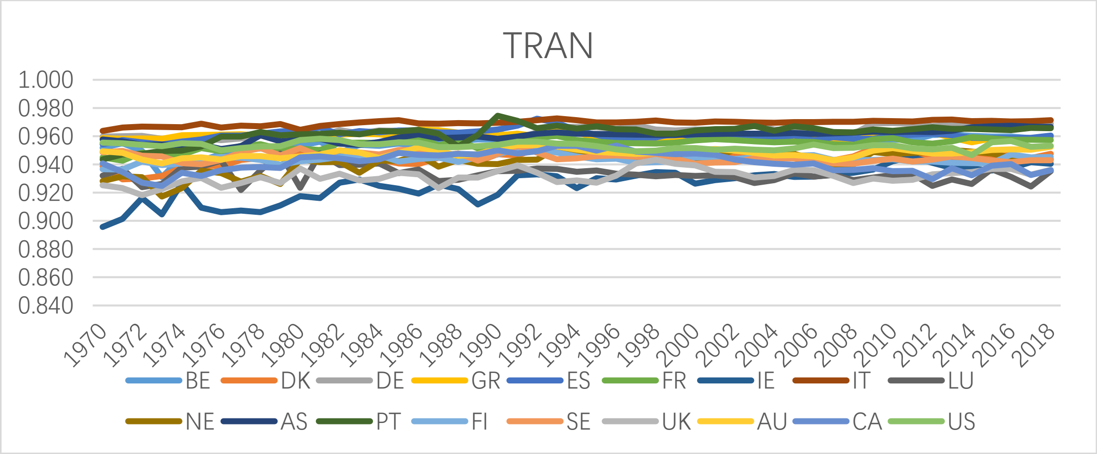


(c) Other machinery

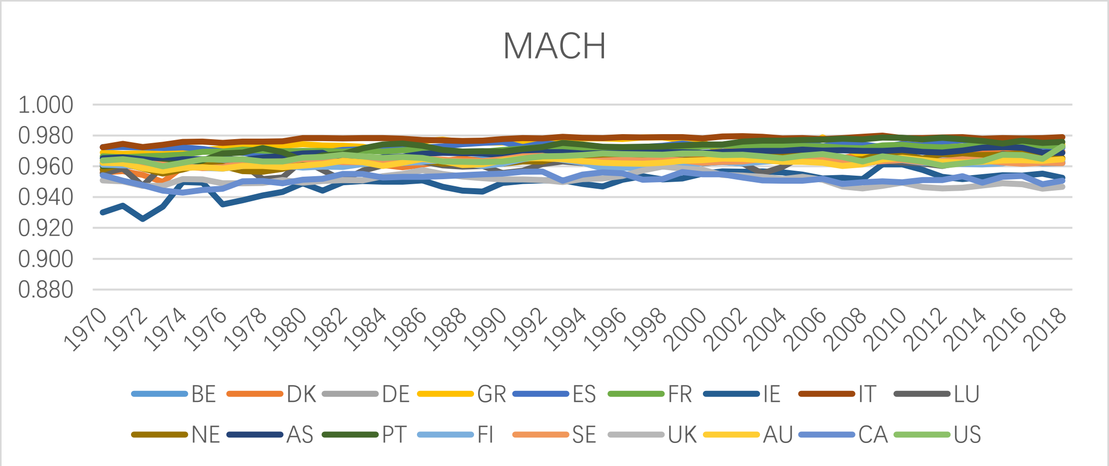
Figure B3. Comparing the relative level of capital stock using alternative depreciation profiles



(a) Non-dwelling building and structure



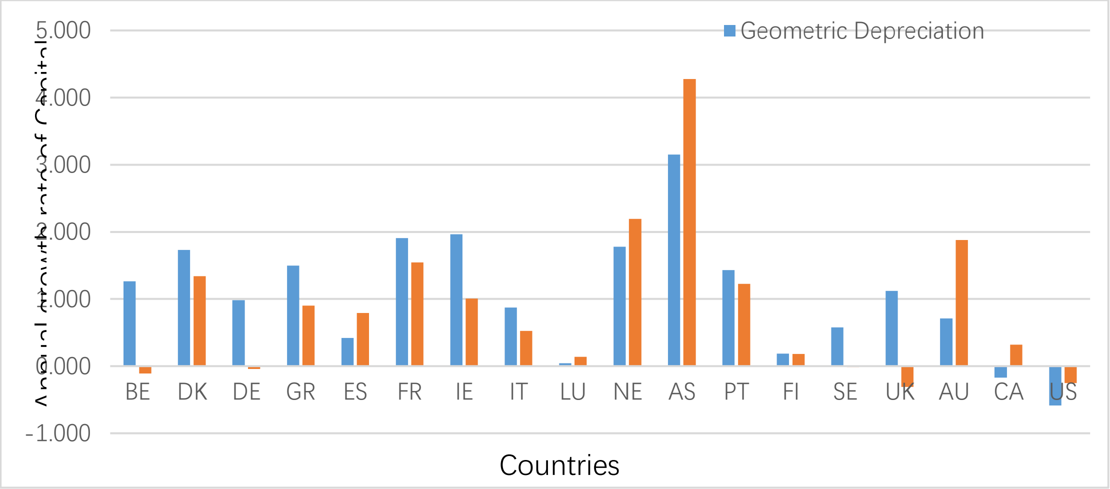
(b) Transportation vehicles



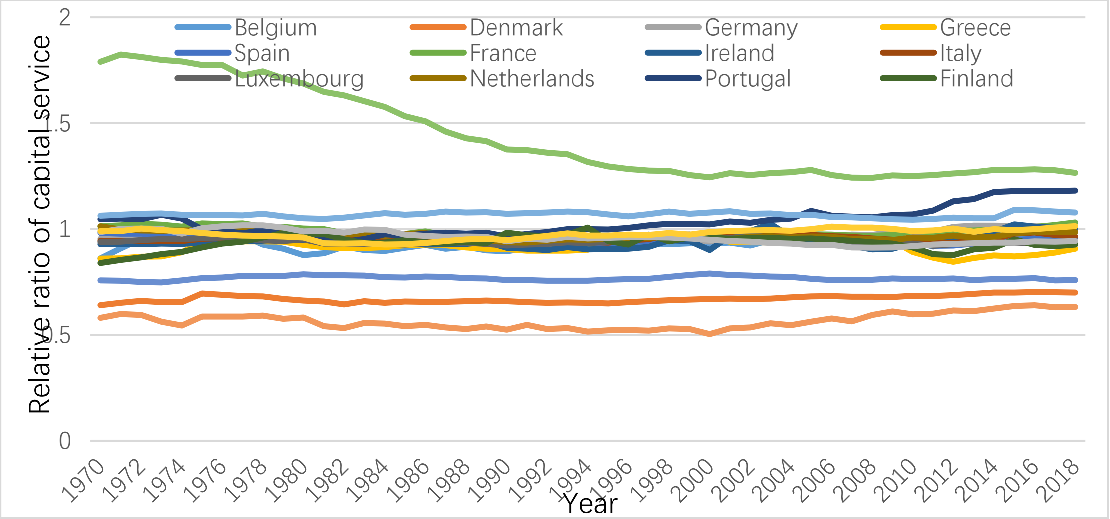
(c) Other machinery

Third, we then consider the change in rental rates obtained from the two assumptions, estimate capital services and aggregate them into aggregate capital service. The results show that there are large differences in both growth rates and relative levels of capital services.

Figure B4. Comparing growth rate and relative level of aggregate capital service using alternative depreciation profiles



(a) Growth rate of aggregate capital services



(b) Relative level of aggregate capital services

Although many people believe that the assumption of geometric depreciation with a fixed service life provides a simple approximation for deriving capital stock and capital service (without losing generality), our empirical results show that such a simplification has a cost. Since the assumption of fixed service life is not realistic in a world with uncertainty, it is necessary to shift towards using the more general hyperbolic depreciation assumption with a variable service life. While the newly proposed approach may not change the growth rate of estimated capital stock, it does affect the estimated relative level of capital stock and affects the aggregation of input through changing the value share.