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Cross-country Consistent Estimation of Agricultural Productivity: The Superlative vs. the Quantity-based Index Approach

Yu Sheng, Eldon Ball and Xinpeng Xu

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Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)

Postal address GPO Box 1563 Canberra ACT 2601
Switchboard +61 2 6272 2010
Facsimile +61 2 6272 2001
Email info.abares@daff.gov.au
Web daff.gov.au/abares

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Foreword

This paper is one of two background papers prepared as part of a collaborative project between the USDA ERS and ABARES of 'Comparing Global Agricultural Productivity: Using Country-level National Account Data'. The other paper is Comparing Agricultural Total Factor Productivity between Australia, Canada and the United States (Sheng et al. 2012).

The project of 'Comparing Global Agricultural Productivity: Using Country-level National Account Data', funded jointly by the USDA ERS, ABARES and RIRDC, has strengthened technical cooperation in areas of common interest in examining productivity level and growth in agriculture across countries and its potential drivers so as to inform public policy making to deal with global food security.

The two background papers supported discussions held by G20 MACs, when Australia took the presidency (June 2014, Brisbane). The discussions led to agreement on common areas of research interest in improving public understanding of how to improve agricultural productivity growth sustainablly in the global context. The project partners the USDA ERS and ABARES intend to use these papers as background information to support collaborative engagement and as reports to OECD/FAO/G20 MACs.

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Abstract

This paper constructs a novel cross-country consistent dataset built upon production accounts at the commodity level for inputs and outputs between Australia, Canada and the United States. Cross-country consistent agricultural productivity is then estimated and compared by using two most widely adopted methods in international comparison, namely the superlative index approach and the quantity-only based index approach. The results show that when price information is available, the superlative index approach always outperforms the quantity-only based index approach in accuracy and consistency of aggregation. This points to the importance of price data collection work for interantional comparison of agricultural productivity.

KEYWORDS Agriculture, International Comparison, Total Factor Productivity

JEL CODE D24, N50, O13

1 Introduction

It has long been recognized that improvement in agricultural productivity is central to deal with the issue of food security that the world faces, given steady growth of population and the scarcity of natural resources available for agricultural production. Between 1960 and 2010, global population increased by 3.7 times and average income per capita more than doubled yet real agricultural prices continued to fall, implying that supply of agricultural products outgrew demand (FAO 2012). This is largely the result of substantial improvement in global agricultural productivity, given constraints in land, the decline in labor supply in the agricultural sector as well as more frequent, unfavourable shocks in weather conditions.

However, agricultural productivity grows unevenly across countries, even though revolution in information and communication technologies paves the way for technology spillovers throughout the world. On one hand, there is an increasing gap in agricultural productivity among developed countries (Ball et al. 2001; Ball et al. 2010; Sheng et al. 2012) and between developed and developing countries (Ludena et al. 2007; Fuglie 2010); there being no evidence of convergence of agricultural productivity between the less productive countries and that in the most productive countries (Fuglie 2012). On the other hand, investment growth in agricultural sector is also unevenly distributed and even more worryingly as there seems to be a general decline in agricultural investment across countries. To improve our understanding of disparity in agricultural productivity and its determinants across countries, it is crucial to obtain and compare cross-country consistent estimation of agricultural productivity levels and growth rates.

Due to its transparency and simplicity, the growth accounting based index method has long been used for cross-country estimation and comparison of agricultural productivity. Previous analyses by using this method can generally be categorised into two groups: the superlative index approach versus the quantity-only based index approach.

Using the method developed by Jorgenson and Nishimizu (1978) and others from ICOP (The International Comparisons of Output and Productivity project) for manufacturing sector, Ball et al. (1997) constructs purchasing power parities (PPPs) for the aggregate input and output of the agricultural sector in ten European countries and the United Sates. Differences in agricultural productivity levels and competitiveness are thus investigated and compared among those countries between 1973 and 1993. This work is extended by Ball et al. (2001) and Ball et al. (2010), which employs the Fisher index adjusted by EKS (Elteto and Koves (1964) and Szulc (1964)) method and the Törnqvist index adjusted by the Caves-Christensen-Diewert (CCD) method (Caves et al. 1982) respectively, to cover more European countries over longer periods. Recently, Fuglie (2010) applied the Törnqvist index method using the FAO data to estimate and compare agricultural total factor productivity (TFP) growth among 171 countries between 1961 and 2006. In general, these studies use the superlative index method in cross-country estimation and comparison of agricultural productivity.

Alternatively, Coelli and Rao (2005) use the distance function approach to derive a quantity-only based index (namely, the Malmquist index) to examine the levels and trends in agricultural output and productivity in 93 countries between 1980 and 2000 using FAO data. Since the quantity-only based index does not require output and input prices, it saves researchers substantial effort and time in data collection work and to circumvent the difficulty in constructing PPPs across countries. Yet, the study is also acknowedged of the weakness of the method in providing unstable productivity estimates. The approach is further extended by

Ludena et al. (2007), Nin-Pratt et al. (2003) and Nin-Pratt and Yu (2009) to forecast long-term cross-country agricultural productivity growth and compare sector-level agricultural productivity across countries.

Although the superlative index and the quantity-only based index can be equally used to provide cross-country productivity estimation in theory (Färe et al. 1994), empirical studies using the two approaches generate rather different results. This phenomenon raised three questions. Do the differences in agricultural productivity estimates come from distinct data sources? Or do these different results come from disparity in the two methodologies? If different results arise from difference in methods, which method performs better empirically?

To answer these questions, we applied both the superlative index and the quantity-only based index to the cross-country consistent data collected from (national accounts of) Australia, Canada and the United States for agricultural productivity estimation and comparison. The results show that different estimation methods may be the key reason that could be used to explain the difference in cross-country productivity estimates. Specifically, the quantity-only based index employs shadow prices derived from the corresponding quantity information as weights. Since the derived shadow prices are usually susceptible to the effects of data noise and can be inconsistent with prior knowledge on market prices and revenue/cost shares, the quantity-only based index may lead to potential problems in measurement.

This paper makes two contributions to the literature on international comparison of agricultural productivity. First, we construct a cross-country consistent dataset built upon production accounts at the very detailed commodity level for inputs and outputs across three countries (namely, Australia, Canada and the United States) for the period 1961 to 2006. This novel dataset provides detailed information on both price and quantity for outputs and inputs at various levels of disaggregation, in comparison with other data sources such as FAO where very limited price information is available. Second, using our newly constructed data set, we compare the empirical performance of two widely used approaches in international comparison of agricultural productivity, i.e., the superlative index and the quantity-only based index. Our results suggest that productivity estimates using the superlative index outperform those using the quantity-only index (i.e. the Malmquist index). The advantage of using the superlative index method is more apparent when it comes to the issue of aggregation consistency: the superlative index method is robust to various levels of disaggregation while the quantity-only index is not. Our finding points to the importance of price data collection work in making international comparison of agricultural productivity.

The rest of the paper is organised as below. Section 2 discusses the superlative index and the quantity-only index when used for productivity estimation across countries. In particular, we derive the condition under which the two approaches are interchangeable. Section 3 defines the production account, and specifies a consistent data compilation process for the three country comparison. Section 4 presents the agricultural productivity estimates obtained by using the two approaches and analyses the condition under which they can be interchangeably used. Section 5 concludes.

2 Methodology: the Superlative Index vs. the Quantity-only Index

Agricultural total factor productivity (TFP) is measured as the ratio of total output (Y_t) to total input (X_t); its growth is measured as the difference between output and input growth rates (estimated using logarithmic differentials with respect to time t).

$$TFP^t = \frac{Y^t}{X^t} \tag{1}$$

$$\frac{dln(TFP^t)}{dt} = \frac{dln(Y^t)}{dt} - \frac{dln(X^t)}{dt} \tag{2}$$

where $Y^t = \sum_i y^t$ and $X^t = \sum_j x^t$ and y^t and x^t are output and input vectors.

There are two types of index methods widely used in cross-country TFP comparison: One is the superlative index (i.e. the Fisher or Törnqvist indexes), which uses the price (or value share) as the weights for output and input aggregation; the other is the quantity-only based index (i.e. the Malmquist index), which uses the distance function to aggregate output and input quantities. The two index methods, though requiring different estimation techniques and data, are generally consistent with each other under certain conditions. This section discusses the two index methods in sequence and show the difference between the two methods when applied to comparing cross-country agricultural productivity.

The Superlative Index

According to the index number theory, the superlative index is a group of index numbers whose underlying transform formula provides a second order differential approximation to any unknown production (or utility) function (Diewert 1976). Although the superlative index family consists of many different fomula (i.e. the Fisher index and the Törnqvist index), using any of these fomula to aggregate output and input requires data on both quantities and prices.

For example, applying the Törnqvist index to measure cross-country consistent agricultural TFP, we need to assume that industry-level agricultural production function satisfies strict neo-classical assumption of separability, Hicks-neutrality of production technology, perfect competition and constant return to scale. Both the direct and indirect approaches can be chosen to aggregate and compare multiple outputs and multiple inputs between two consecutive periods in each country.

The direct approach is to use revenue share as weights for output aggregation and cost share as weights for input aggregation, such that the Törnqvist index based measure of TFP change between two consecutive periods can be written as:

$$T_{TFP}^{t,t+1} = \frac{T_y^{t,t+1}(p^{t,t+1}, y^{t,t+1})}{T_x^{t,t+1}(w^{t,t+1}, x^{t,t+1})} \qquad (3)$$

with

$$T_y^{t,t+1}(p^{t,t+1}, y^{t,t+1}) = \prod_{i=1}^{n} \left(\frac{y_i^{t+1}}{y_i^t}\right)^{\frac{1}{2}*[R_i^t + R_i^{t+1}]} \qquad (4)$$

$$T_x^{t,t+1}(w^{t,t+1}, x^{t,t+1}) = \prod_{j=1}^{m} \left(\frac{x_j^{t+1}}{x_j^t}\right)^{\frac{1}{2}*[S_j^t + S_j^{t+1}]} \qquad (5)$$

where $R_i^t = p_i^t y_i^t / \sum_i p^t y^t$ is the revenue share of the ith output and $S_j^t = w_i^t x_i^t / \sum_i w^t x^t$ is the cost share of the jth input at time t. Implicit in the formula are the price vectors of output p^t and of input w^t.

Alternatively, an indirect approach can be used whereby aggregate output (input) quantity equals the gross value of outputs (inputs) divided by a corresponding price index. When the production account data used for estimation satisfy the accounting identity , direct and indirect quantity estimates are equivalent for a superlative index and can be used exchangable (Jorgenson and Griliches 1967).

Finally, the measured TFP by using the supperlative index requires to be adjusted for transitivity so as to ensure its cross-country comparibility. In doing so, domestic prices of various outputs and inputs, which are not directly compariable across countries, need to be converted into international prices using the assumption of purchasing power parity (PPP). Ball et al. (1997a) shows that the Törnqvist index retains a high degree of characteristicity when combined with the Caves-Christensen-Diewert (1985, or the CCD approach) formula for transitivity adjustment (Drechsler 1973). Specifically, a cross-country compariable price index for outputs obtained by using the CCD approach can be written as:

$$\ln P_{uv} = \frac{1}{2} * \sum_{i=1}^{n} \left(s_u + \frac{1}{C} * \sum_{c=1}^{C} s_c\right)\left(\ln p_{ui} - \overline{\ln p_{cı}}\right) - \frac{1}{2} * \sum_{i=1}^{n} \left(s_v + \frac{1}{C} * \sum_{c=1}^{C} s_c\right)\left(\ln p_{vi} - \overline{\ln p_{cı}}\right) \qquad (6)$$

where $s_f = p_{fi}\, y_{fi} / \sum_{i=1}^{n} p_{fi}\, y_{fi}$, $f = u, v, c$ representing countries and $\overline{\ln p_ı^k} = \frac{1}{C} * \sum_{i=1}^{n} p_i^k$ representing the average price with p_{vi}representing the price of the i-th output (input) in the v-th country ($j = 1,2, \dots, I$), c_i is the revenue (cost) share of the i-th commodity output (input), $\bar{c}_i = \frac{1}{I}\sum_{c=1}^{C} c_{ic}$ and $\overline{\ln p_ı} = \frac{1}{I}\sum_{c=1}^{C} \ln p_{ic}$., and $\overline{\ln p_i}$ is their mean. I represents a general index for current country v, with u as the base country. A similar formula can also be derived for the cross-country compariable price index for inputs.

The Quantity-only Based Index

Compared tothe superlative index which requires data on both price and quantity, using the quantity-only based index to measure cross-country consistent agricultural TFP only requires data on output and input quantities. To aggregate outputs and inputs, a common shared technological frontier (i.e. a trans-log production function) is assumed and the distance function can be used to convert multiple outputs and multiple inputs into a single measure of output-input ratio using the data envelope analysis.

For example, using the Malmquist index to measure the TFP change between two consecutive periods is equivalent to calculate the ratio of the distance of any multiple output-input combination (or data point) relative to a common shared technological frontier (or the assumed production function) (Färe et al. 1994), such that

$$M_{TFP}^{t,t+1} = [M_0^t * M_0^{t+1}]^{1/2} = [\frac{D_0^t(x^{t+1},y^{t+1})}{D_0^t(x^t,y^t)} * \frac{D_0^{t+1}(x^{t+1},y^{t+1})}{D_0^{t+1}(x^t,y^t)}]^{1/2} \quad (7)$$

The agricultural TFP growth measure, as Equation (2), is defined as the geometric mean of two Malmquist indexes, M_0^t and M_0^{t+1}, with each using the technology frontier in t and t+1 respectively. D(. , .) is a non-parametric distance function

Färe et al. (1994) showed that the TFP index thus measured (Equation (7)) could be further decomposed into an efficiency change component and a technical change component, and the decomposition could be applied to the different period-based Malmquist indexes such that

$$M_{TFP}^{t,t+1} = \frac{D_0^{t+1}(x^{t+1},y^{t+1})}{D_0^t(x^t,y^t)} * [\frac{D_0^t(x^{t+1},y^{t+1})}{D_0^{t+1}(x^t,y^t)} * \frac{D_0^t(x^t,y^t)}{D_0^{t+1}(x^t,y^t)}]^{1/2} \quad (8)$$

The efficiency change component of the Malmquist indexes measures the change in how far observed production is from maximum potential production between period t and t+1. The technical change component captures the shift of technology between the two periods. The two components add up together to form the measure of TFP and they could be measured by using either the input-based or output-based Malmquist indexes. Note that since there is no prior-price information required in the estimation of quantity-only based index, the TFP measure based on the Malmquist index does not require the conversion of PPP for the transitivity adjustment.

Comparison between the Two Indices

Both the superlative index and the quantity-only based index can approximate any flexible function form, and theoretically they mirror each other in TFP measurement under certain conditions. To see how the two approaches link to each other, we start with analysing a generalised production function describing the possibilities for the transformation of inputs x^t into outputs y^t (where $x^t \in R^m$ and $y^t \in R^n$).

$$L^t=\{(y^t, x^t): \text{such that } x^t \text{ can produce } y^t)\} \quad (9)$$

Following Färe et al. (1998), we assume that the production technology satisfies the usual set of axioms: closedness; non-emptiness; scarcity; and no free lunch. Under these assumptions, the data envelope analysis (DEA) approaches and its related linear programming can be used to derive the TFP measure using either the superlative index or the quantity-only based index.

On one hand, the input oriented distance function (corresponding to (7)) at t is defined as the minimum proportional contraction of input vector x^t given output y^t such that $D_0^t(x^t, y^t) = \min\{\theta: (\theta x^t, y^t) \in L^t\}$ where θ is the coefficient which multiplies x^t to get a production frontier y^t. This distance function can thus be solved by using the DEA approach as

$$min_{\theta,\lambda}\theta_0$$

s.t.

$\sum_{k=1}^{r} y_{ki}\lambda_k - y_{0i} \geq 0 \quad \text{with } i = 1, \dots, m$

$x_{0j}\theta - \sum_{k=1}^{r} x_{kj}\lambda_k \geq 0 \text{ with } j = 1, \dots, n$

$\lambda \geq 0$ (10)

where k represents observations defining production possibility set, i represents m outputs and j represents n inputs. The efficiency score obtained (θ_0) takes values between 0 and 1, with 1 indicating that the data point is at the frontier. Equation (10) is known as the envelope form of the DEA approach that can be used to measure the quantity-only based (or Malmquist) index.

Alternatively, an equivalent dual approach can also be derived from the envelope form (Kousmanen et al. 2004) to measure the price weighted superlative index. Specifically, the dual approach measures efficiency as the ratio of a weighted sum of all outputs over a weighted sum of all inputs (consistent with Equations (3)-(5)) such that

$$\frac{max_{p,w} \sum_{i=1}^{m} p_i y_{0i}}{\sum_{j=1}^{n} w_j x_{0j}}$$

s.t.

$\sum_{i=1}^{m} p_i y_{ki} / \sum_{j=1}^{n} w_j x_{kj} \leq 1 \qquad \text{with } k = 1, \dots, r$

$p_i, w_j \geq 0 \qquad \text{with } i = 1, \dots, m; j = 1, \dots, n$ (11).

As in Coelli and Rao (2001), we need to impose the unit condition (sum ($w_j x_{kj}$)=1) to solve Equation (11). This leads to a condition that equalize Equation (3) and to Equation (7), such that

$$D_x^t(x^t, y^t) = \max_{\rho,\omega}\{\frac{\rho y^t}{\omega x^t} : \frac{\rho y^t}{\omega x^t} \leq 1 \forall (y^t, x^t) \in L^t\} \quad (12)$$

Based on Equation (12), the superlative index TFP measure and the quantity-only based index TFP measure share the equivalent formulation (Kuosmanen et al. 2004) if and only if the retrieved implicit prices are the same as market prices and all observations locate at the production frontier. The interpretation is that input-output relationship captures the 'return to the dollar' (Georgescu-Roegen 1951) at the 'most favourable' prices, subject to a normalising condition that no feasible input-output vector yields a return to the dollar higher than unity at those prices. Correspondingly, the optimal weights ρ and ω are respectively output k and input j prices with respect to technology L^t. As such, the superlative index and the quantity-only based index only differ (from each other) in terms of the implicit/explicit prices used as weights for aggregation.

Following the above discussion, we apply both the superlative index and the quantity-only based index to the three country comparison data to examine how well these conditions are satisfied in practice.

3 Variable Definition and Data Source

Production accounts for agriculture are compiled for the United States by the U.S. Department of Agriculture Economic Research Service (USDA ERS), for Canada by Agriculture and Agri-food Canada and for Australia by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES). These accounts are the primary sources of data that we use to construct our cross-country consistent dataset for the United States, Canada and Australia between 1960 and 2006.

Our dataset consists of three subsets corresponding to three different levels of aggregation. The first is at the highest level of aggregation, namely two major agricultural outputs (crop and livestock products) and four major inputs (land, labour, capital and intermediate inputs). The second is at the medium level of aggregation where there are six outputs (coarse grains, oil crops, vegetables, fruits and nuts, other crops and livestocks) and ten inputs (land, non-residential building and structure, transportation vehicles, plant and machinery, labour, fuel, fertilizers, crop chemicals and medicines, services, other materials and other services). The third is at a relatively fine level of disaggregation where there are sixteen outputs (coarse grains, oil crops, vegetables, fruits and nuts, other crops, beef and cattle, hog/pig, sheep and lamb, milk and dairy products, chicken, turkey and other poultry, eggs, wool, honey and wax, and other livestock products) and ten inputs (as in the second dataset). Note that to calculate capital stock, we use the earliest data available for capital investment in each country. A brief description of the data sources for each country is outlined here and a complete variable list is provided in Appendix A.

United States

We obtained most of our data for the United States from the US Census of Agriculture and the US Agricultural Resource and Management Survey. The USDA ERS has available state-level data on farm cash receipts. We also obtained agricultural prices data from the USDA for most outputs and intermediate inputs. We used these data to construct aggregate agricultural output values.

Data for capital investment were collected from the Bureau of Economic Analysis and information for deflators for transport vehicles from the Bureau of Labour Statistics. We obtained data for the implicit price deflator for non-dwelling buildings and structures from the US National Accounts.

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

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

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 USDA agricultural prices database.

Canada

Production data were not 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 aggregate output estimates.

A capital investment data series was compiled for the period 1926 to 2006. As the data series for early and recent years were not available, some imputations were applied both at the beginning and end of the investment series. Investment deflators (or price index) between 1926 and 1935 were constructed with import price data taken from Trade of Canada. For other years, disaggregated deflators for each asset grouping are available directly from the national account statistics.

The prices of land were sourced from Statistics Canada, as part of the Agricultural Value-Added Account. All data series started from 1981, with land area sourced from the Canadian Agricultural Census and land price from the Canadian Agricultural Value-Added Account. They were backcast using a fixed ratio.

Data on intermediate inputs were obtained from the Supply Disposition Balance Sheets and other industry statistics. Individual price indexes were 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.

Hired labour was estimated with data from the Canadian Labour Force Survey and the Population Census of Canada. Estimation of self-employed labour input (defined as the number of hours worked) was based on 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 Canadian Labour Force Survey data for 1991 onwards. The input of unpaid family members was estimated as a proportion of self-employed labour input.

Australia

Agricultural output data were sourced primarily from the ABARES Agricultural Commodity Statistics. For smaller commodity items, where price data were not available, a general ABARES farm prices received index was used.

Capital investment data were taken from the Australian Bureau of Statistics National Accounts Database and backcast to 1860 using data from Butlin (1977) and Powell (1974). Since data for the deflator for transportation vehicles are not available between 1920 and 1960, it is assumed to be the same as that for plant and machinery.

The Australian agricultural census was used to estimate land area. Land prices were estimated using 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 the hedonic modelling exercise.

Intermediate inputs (including total expenditure and price indexes) were sourced from ABARES Agricultural Commodity Statistics.

Labour input was estimated as total number of hours worked, calculated by multiplying the number of workers by the average number of hours worked and the number of weeks. The average hours worked was obtained from the Australian Bureau of Statistics Population Census and it is assumed that there are 52 weeks a year.

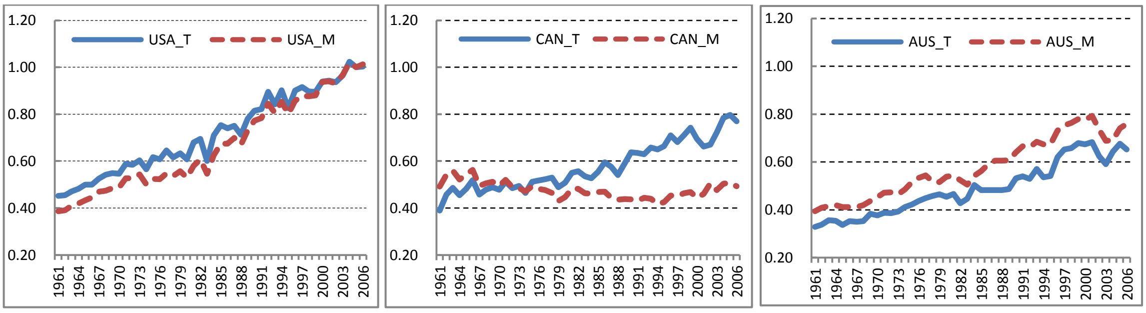
4 Empirical Results

Agricultural TFP Estimates for Australia, Canada and the United States

We first make use of the aggregate level dataset which consists of two outputs and four inputs to estimate cross-country consistent agricultural TFP for Australia, Canada and the United States respectively. Between 1961 and 2006, the estimated agricultural TFP indices for Australia, Canada and the United States have generally been increasing though unevenly across countries and over time, when holding the US agricultural TFP level in 2005 as the numeraire (Figure 1). This pattern of rising agricultural TFP holds for the TFP estimates obtained from using both the Törnqvist and Malmquist index approaches (**Error! Reference source not found.**).

Figure 1 Cross-country consistent estimation of levels of agricultural TFP

(A)The United States (B) Canada (C) Australia



Note: The three figures display levels of agricultural TFP for the three countries. "USA", "CAN", and "AUS" denote the United States, Canada and Australia respectively. The last letter of each indicator, " _T" and "_M" stand for results from the Törnqvist and Malmquist index approaches respectively. Note that the level of agricultural TFP in the US in 2005 is set to one (as base country-year).

Table 1 Total plantation area, by jurisdiction, 2011–12

	USA	CAN	AUS
Tonqvist index (2x4)	1.798	1.242	1.644
Malmquist index (2x4)	2.160	-0.300	1.610

Note: (2x4) denotes the model used which has two outputs and four inputs (see the text for details).
Source: Authors' own estimation.

Specifically, based on the Törnqvist index approach, the annual agricultural TFP of the United States grows at the rate of 1.8 per cent a year, followed by that of Australia (1.6 per cent a year) and then by that of Canada (1.2 per cent a year) between 1961 and 2006. Alternatively, calculated by using the Malmquist index, the annual agricultural TFP growth rate for the United States is 2.2 per cent a year for the same period, which is much higher than that for Australia (1.6 per cent a year) and that for Canada (-0.3 per cent a year).

Although the results obtained from using both index approaches display similar trend of TFP growth, there are marked differences in magnitudes of TFP levels between the Törnqvist TFP index and the Malmquist TFP index for the United States, Canada and Australia. This phenomenon deserves some further discussion. First, with the same data, the levels of the TFP index estimated based on the Malmquist index approach are generally lower than those estimated using the Törnqvist index approach for the United States while for Australia the results from the Malmquist index approach are generally higher than those from the Törnqvist index approach. For Canada, TFP estimates from the two approaches show a mixed pattern: levels of TFP based on the Törnqvist index approach are lower than those based on the Malmquist index approach for the initial years but higher for later years.

Second, the differences in estimated TFP levels using the two different approaches also lead to systematic differences in TFP growth. Over the period 1961 to 2006, the TFP growth rate estimated by using the Malmquist index is higher than that estimated by using the Törnqvist index for the United States while the results from the Malmquist index is lower than those estimated by using the Törnqvist index for both Canada and Australia. In particular, the TFP growth rate for Canada estimated by using the Malmquist index becomes negative (**Error! Reference source not found.**).

The detailed year-by-year TFP results for the three countries are also reported in Table 2. Note that when using the Malmquist index for TFP estimates, the input-orientation and the output-orientation assumptions generate almost the same results (Table 3). Thus, to simplify the analysis, the discussion on results from the Malmquist TFP index hereafter will focus on those based on the input-orientation assumption only while leaving the results from the Malmquist TFP index based on the output-orientation assumption as a robustness check.[1]

Table 4 Annual agricultural TFP in the US, Canada and Australia

	Törnqvist/CCD			Malmquist/In-oriented			Malmquist/Out-oriented		
Year	USA	CAN	AUS	USA	CAN	AUS	USA	CAN	AUS
1961	0.4520	0.3890	0.3290	0.4516	0.4536	0.3361	0.4516	0.4496	0.3346
1962	0.4550	0.4570	0.3380	0.4547	0.5330	0.3457	0.4547	0.5284	0.3442
1963	0.4710	0.4860	0.3560	0.4713	0.5673	0.3637	0.4713	0.5624	0.3622
1964	0.4820	0.4540	0.3540	0.4819	0.5300	0.3619	0.4819	0.5254	0.3603
1965	0.4990	0.4810	0.3370	0.4995	0.5619	0.3437	0.4995	0.5570	0.3422
1966	0.5000	0.5190	0.3530	0.4997	0.6054	0.3602	0.4997	0.6001	0.3586

[1] The Malmqvist TFP index based on the output-orientation assumption is available from authors upon request.

1967	0.5250	0.4570	0.3510	0.5252	0.5336	0.3582	0.5252	0.5290	0.3566
1968	0.5420	0.4770	0.3530	0.5416	0.5571	0.3608	0.5416	0.5522	0.3592
1969	0.5490	0.4890	0.3830	0.5494	0.5711	0.3912	0.5494	0.5661	0.3895
1970	0.5460	0.4770	0.3770	0.5458	0.5570	0.3849	0.5458	0.5521	0.3832
1971	0.5880	0.5120	0.3880	0.5881	0.5980	0.3963	0.5881	0.5928	0.3946
1972	0.5840	0.4840	0.3860	0.5841	0.5651	0.3943	0.5841	0.5602	0.3925
1973	0.6040	0.4940	0.3930	0.6036	0.5765	0.4016	0.6036	0.5715	0.3998
1974	0.5660	0.4640	0.4110	0.5657	0.5420	0.4202	0.5657	0.5373	0.4184
1975	0.6170	0.5120	0.4220	0.6168	0.5981	0.4311	0.6168	0.5929	0.4292
1976	0.6070	0.5170	0.4380	0.6072	0.6036	0.4470	0.6072	0.5984	0.4451
1977	0.6460	0.5230	0.4490	0.6462	0.6104	0.4586	0.6462	0.6051	0.4566
1978	0.6160	0.5300	0.4590	0.6157	0.6186	0.4686	0.6157	0.6132	0.4666
1979	0.6340	0.4890	0.4650	0.6336	0.5702	0.4748	0.6336	0.5652	0.4727
1980	0.6070	0.5070	0.4540	0.6073	0.5919	0.4636	0.6073	0.5868	0.4616
1981	0.6800	0.5500	0.4670	0.6798	0.6418	0.4771	0.6798	0.6363	0.4750
1982	0.6950	0.5570	0.4280	0.6947	0.6499	0.4367	0.6947	0.6443	0.4348
1983	0.6010	0.5350	0.4460	0.6010	0.6239	0.4553	0.6010	0.6185	0.4533
1984	0.7100	0.5270	0.5040	0.7098	0.6151	0.5146	0.7098	0.6097	0.5124
1985	0.7540	0.5540	0.4820	0.7540	0.6464	0.4924	0.7540	0.6408	0.4903
1986	0.7400	0.5960	0.4820	0.7404	0.6952	0.4928	0.7404	0.6891	0.4906
1987	0.7500	0.5760	0.4830	0.7502	0.6726	0.4930	0.7502	0.6667	0.4908
1988	0.7130	0.5400	0.4830	0.7129	0.6303	0.4928	0.7129	0.6248	0.4907
1989	0.7800	0.5900	0.4870	0.7801	0.6890	0.4975	0.7800	0.6830	0.4953
1990	0.8140	0.6370	0.5320	0.8141	0.7432	0.5439	0.8141	0.7367	0.5415
1991	0.8210	0.6350	0.5400	0.8212	0.7411	0.5520	0.8212	0.7346	0.5496
1992	0.8950	0.6290	0.5290	0.8951	0.7345	0.5406	0.8951	0.7281	0.5382
1993	0.8430	0.6580	0.5710	0.8426	0.7683	0.5832	0.8426	0.7616	0.5806
1994	0.9020	0.6500	0.5360	0.9023	0.7585	0.5470	0.9023	0.7519	0.5446
1995	0.8250	0.6630	0.5410	0.8250	0.7743	0.5525	0.8250	0.7676	0.5501

1996	0.9010	0.7100	0.6200	0.9013	0.8281	0.6336	0.9013	0.8209	0.6308
1997	0.9150	0.6820	0.6520	0.9152	0.7956	0.6657	0.9152	0.7886	0.6628
1998	0.8970	0.7090	0.6580	0.8966	0.8280	0.6718	0.8966	0.8207	0.6689
1999	0.8950	0.7420	0.6790	0.8950	0.8664	0.6933	0.8950	0.8588	0.6902
2000	0.9390	0.6950	0.6740	0.9393	0.8108	0.6888	0.9393	0.8037	0.6858
2001	0.9430	0.6620	0.6830	0.9427	0.7730	0.6980	0.9427	0.7663	0.6949
2002	0.9370	0.6700	0.6240	0.9368	0.7817	0.6375	0.9368	0.7749	0.6347
2003	0.9650	0.7230	0.5910	0.9649	0.8433	0.6036	0.9649	0.8360	0.6010
2004	1.0240	0.7850	0.6430	1.0239	0.9161	0.6564	1.0239	0.9081	0.6535
2005	1.0000	0.7970	0.6770	1.0000	0.9298	0.6911	1.0000	0.9217	0.6881
2006	1.0030	0.7700	0.6520	1.0033	0.8985	0.6663	1.0033	0.8907	0.6634

Note: The level of TFP for the US=1 in 2005 (base country-year).
Source: Authors' own estimation.

Differences in the Törnqvist and the Malmquist TFP indexes: weights and shares

Why do the TFP estimates obtained by using the Törnqvist and the Malmquist TFP indices differ from each other? As discussed in Section 2, the differences in the two indexes may lie in that they use different weights for aggregation, as all the three countries should be treated as always locating at the production frontier. Specifically, the Törnqvist index employs real market prices (revenue/cost share) as weights for aggregating various outputs and inputs, while the Malmquist index employs implicit prices (retrieved from the corresponding quantities) as weights. To explore this point from an empirical perspective, we estimate and compare the output/input shares by using the two approaches.

Using real market prices (adjusted for the purchasing power parity, PPP), average output shares in total revenue and input shares in total expenditures are estimated for the United States, Canada and Australia. These shares are then used as weights for aggregating the Törnqvist quantity index in each country respectively (Table 5). For consistency, we still use the aggregate level data for two outputs (i.e. crop and livestock products) and four inputs (i.e. land, labour, capital and intermediate inputs) for all three countries.

As shown in Table 6, in terms of outputs, crop products on average accounted for around half of the total revenue for all the three countries with the adjustment of PPP prices between 1961 and 2006. In terms of inputs, intermediate inputs generally accounted for the largest expenditure shares, followed by capital and labor, though there are some disparities across countries. In the United States and Canada, for example, intermediate inputs on average accounted for 55 per cent and 56 per cent of total expenditures, followed by labor (25 per cent for the United States and 18 per cent for Canada), capital (11 per cent for the United States and 17 per cent for Canada) and land (9 per cent for the United States and for Canada). In Australia, intermediate inputs on average accounted for 38 per cent of total expenditure, followed by capital (32 per cent), labor (20 per cent) and land (10 per cent).

Table 7 Output/input share and real prices in the Törnqvist index: average between1960-2006

	USA	CAN	AUS	Real Price
Output Share in Total Revenue				
Crops Share (%)	55.2	52.0	49.5	1.022
Livestock Share (%)	44.8	48.0	50.5	0.724
Input Share in Total Expenditure				
Land Share (%)	8.6	8.8	10.2	0.432
Capital Share (%)	11.3	17.0	31.5	0.715
Labor Share (%)	24.8	18.3	19.9	0.298
Intermediate Inputs Share (%)	55.2	55.9	38.3	0.700

Note: The real price is estimated by using the arithmetic average of the PPP prices.
Source: Authors' own estimation.

Since the Malmquist index is a quantity-only based index which only uses information on quantity, prices of outputs and inputs and their corresponding revenue and cost shares in the Malmquist index are not directly available. To compare them with the real market prices of outputs and inputs as well as their revenue and cost shares from the Törnqvist index, we retrieve them by simulating the maximisation process with the corresponding quantity information. As shown in Table 8, the implicit output and input shares implicitly used by the Malmquist index showed significantly different patterns from the share estimated by using the market prices. On the output side, crop products only accounted for 30 to 40 per cent of total revenue for the three countries between 1961 and 2006. On the input side, land accounted for the largest share of total expenditure while intermediate inputs held the smallest share. The significant difference between the retrieved revenue/cost share from the Malmquist index (Table 9) and the real revenue/cost share estimated based on the Törnqvist index (Table 10) implies that the implicit prices of various outputs and inputs underlying the assumed distance function could be quite different from the corresponding market prices. These results suggest that cross-country TFP estimates and comparison using the quantity-only based index could be potentially biased.

Table 11 Output/input share and real prices in the Törnqvist index: average between1960-2006

	USA	CAN	AUS	Implicit Price
Output Share in Total Revenue				

Crops Share (%)	32.5	40.4	27.9	0.389
Livestock Share (%)	67.5	59.6	72.1	0.495
Input Share in Total Expenditure				
Land Share (%)	59.1	48.0	45.2	2.237
Capital Share (%)	19.9	18.3	20.8	2.472
Labor Share (%)	12.6	19.3	15.8	0.312
Intermediate Inputs Share (%)	8.4	14.4	18.3	0.741

Note: This table shows results from the average between1960-2006.
Source: Authors' own estimation.

Aggregation Consistency Test for the Two Approaches

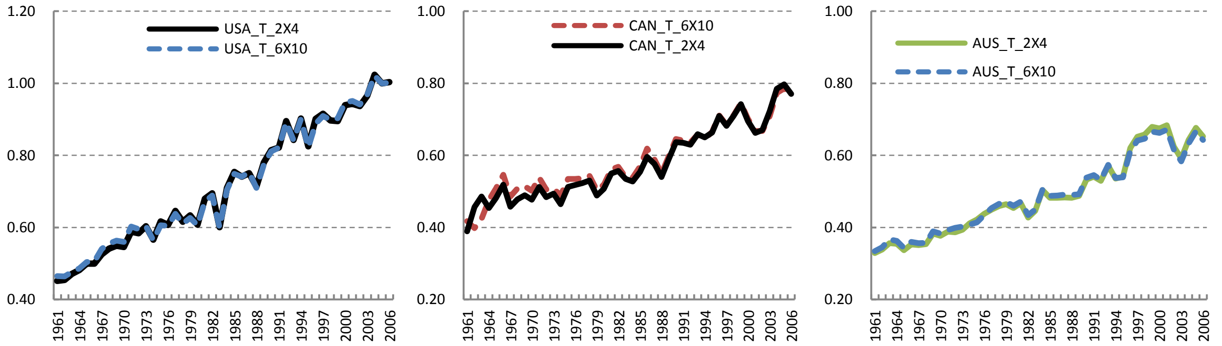
Using the same data, we report, in the above section, that differences in TFP estimates obtained from the superlative index and the quantity-only based index can be traced back to their use of different weights for output and input aggregation. The superlative index uses real market price to calculate weights while the quantity-only based index uses derived price information, which cause the quantity-only based index to generate potentially biased estimates. Yet, more importantly, the two types of index approaches may also differ in performance when output and input data are organised at different levels of aggregation.

As is well known, neither the superlative index (in particular, the Tornqvist indexes) nor the quantity-only based index (i.e. the Malmquist index) satisfies the addative axiom and thus should be consistent in aggregation (Balk 2005). Yet, it is still not known which approach is more sensitive to different levels of aggregation empirically. For international comparison of agricultural productivity, we would prefer an approach that is relatively more stable to various levels of aggregation (aggregation consistent).

To quantify the impact of output and input disaggregation on performance of the two different index approaches, we further estimate agricultural TFP growth for the three countries between 1961 and 2006 by applying the Törnqvist index and the Malmquist index to three models with data at different levels of aggregation (including the 2-output and 4-input model, the 6-output and 10-input model and the 16-output and 10-input model).

Figure 2 Comparison of estimated Törnqvist TFP growth: 2x4 model vs. 6x10 model

(A)The United States (B) Canada (C) Australia



Note: The three figures display levels of agricultural TFP for the three countries. “USA”, “CAN”, and “AUS” denote the United States, Canada and Australia respectively. The last letter of each indicator, “ _T”, stands for the Törnqvist index. The number of each indicator, “ _2x4” and “_6x10”, denote results from 2-output and 4-input model and 6-output and 10-input model respectively. Note that the level of agricultural TFP in the US in 2005 is set to one (as base country-year).
Source: Authors' own estimation.

Figure 3 provides a visual plot of the estimated Törnquist TFP index that applies to two different levels of aggregation (2-output and 4-input versus 6-output and 10-input) for the three countries respectively. The estimated Törnquist TFP index series for both levels of disaggregation overlap substantially for all three countries, indicating that it is not sensitive to levels of disaggregation. We further report in Table 12 the average growth rate of Törnquist TFP. As the level of disaggregation increases (from 2-output and 4-input to 6-output and 10-input and then to 16-output and 10-input), the estimated annual Törnquist TFP growth rates become lower for all three countries. For example, the estimated annual Törnquist TFP growth rate in the 2-output and 4-input case is about 1.8 per cent while it decreases to 1.74 for in the 16-output and 10-input case for the United State. Are these decreases in estimated Törnquist TFP growth rates along with the levels of disaggregation significant or not for all three countries? A simple calculation of the root mean squared coefficient of variance gives a range between 0.02 to 0.06 (close to zero), implying that estimated Törnquist TFP for different levels of aggregation is quantitatively the same. The result suggests that Törnquist TFP index is aggregation consistent.

Table 13 Comparison of the estimated Törnqvist TFP growth with various levels of disaggregation

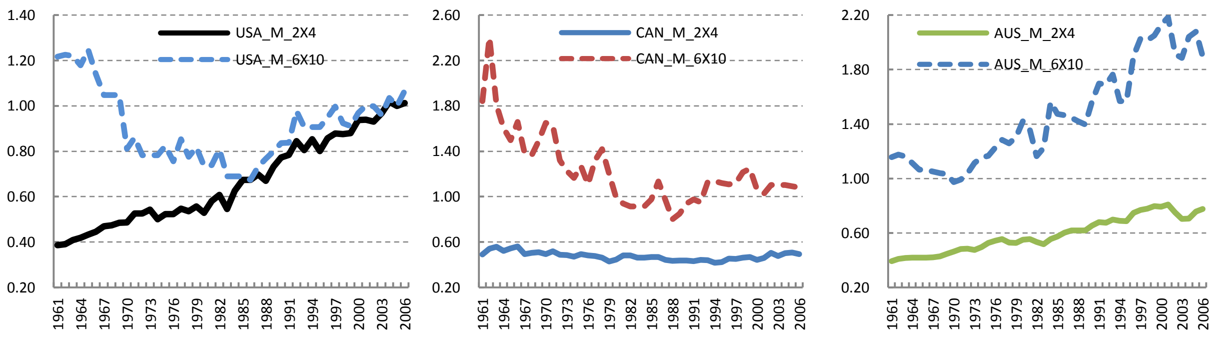
	USA	CAN	AUS
Törnqvist 2x4	1.798	1.242	1.644
Törnqvist 6x10	1.750	1.180	1.560
Törnqvist16x10	1.743	1.096	1.453
Root mean squared coefficient of variance (RMSD)	0.02	0.06	0.06

Note: (2x4) denotes the model used which has two outputs and four inputs; (6x10) denotes the model used which has six outputs and ten inputs; (16x10) denotes the model used which has sixteen outputs and ten inputs. The unit in the table is percent. It represents the annual Törnqvist TFP growth rate.
Source: Authors' own estimation.

In contrast, the estimated Malmquist TFP and its growth rates for all three countries are not aggregation consistent. As plotted in Figure 4, the estimated Malmquist TFP index series for both levels of disaggregation diverge substantially, indicating that estimated Malmquist TFP index is very sensitive to levels of disaggregation.

Figure 5 Comparison of estimated Malmquist TFP growth: 2x4 model vs. 6x10 model

(A)The United States (B) Canada (C) Australia



Note: The three figures display levels of agricultural TFP for the three countries. “USA”, “CAN”, and “AUS” denote the United States, Canada and Australia respectively. The last letter of each indicator, “ _M”, stands for the Malmquist index. The number of each indicator, “ _2x4” and “_6x10”, denote results from 2-output and 4-input model and 6-output and 10-input model respectively. Note that the level of agricultural TFP in the US in 2005 is set to one (as base country-year).
Source: Authors' own estimation.

Table 14 reports that average growths of Malmquist TFP index at different levels of aggregation for the three countries. The estimated annual Malmquist TFP growth rate in the 2-output and 4-input case is about 2.16 per cent while it decreases to 0.38 for in the 16-output and 10-input case for the United State. The case of Canada is even more revealing. Based on the model of 2-output and 4-input, the estimated annual Malmquist TFP growth rate for Canada is negative (-0.30 per cent) but it turns to positive (1.08 per cent) when estimated at a much finer level of disaggregation (the 16-output and 10-input case). Are the Malmquist TFP series estimated with different levels of aggregation statistically different? The root mean squared coefficient of variance gives a range between 0.7 for Australia to 6.89 for Canada which is at least 10 times larger than those obtained from the Törnquist TFP estimates. This finding implies that the Malmquist index is not aggregation consistent empirically.

Compared to the Törnquist index, the poor performance of the Malmquist index in aggregation deserve some discussion. Since both index methods provide good approximation for the aggregation function form, the difference may still lie in the prices or shares used as weights for aggregation. In particular, when output and input aggregates are divided into sub-aggregates, there will be more dimensions to be considered when the data envelope analysis is applied to estimating the distance function. The implicit prices (and weights) are more likely to deviate from the market prices at the disaggregate level (alternatively, there is a lot of offsetting as it gets to more aggregated level). As such, changes in the weight system asymmetrically at different levels of aggregation levels lead to significant differences in Malmquist TFP estimates.

Table 15 Comparison of the estimated Törnqvist TFP growth with various levels of disaggregation

	USA	CAN	AUS
Malmquist 2x4	2.160	-0.300	1.610
Malmquist 6x10	0.900	-1.300	0.370
Malmquist 16x10	0.380	1.080	0.760
Root mean square coefficient of variation (RMSD)	0.80	6.89	0.69

Note: (2x4) denotes the model used which has two outputs and four inputs; (6x10) denotes the model used which has six outputs and ten inputs; (16x10) denotes the model used which has sixteen outputs and ten inputs. The unit in the table is percent. It represents the annual Malmquist TFP growth rate.
Source: Authors' own estimation.

Robustness Check

To test whether differences in performance between Törnquist TFP and Malmquist TFP comes from the choice of specific functional form, we re-do the above exercise by using the Fisher index and the output-oriented Malmquist index and compare the results with those obtained from using the Törnquist index and the input-oriented Malmquist index. The Fisher TFP performs similar as the Törnquist TFP and the input-oriented Malmquist TFP performs similar as the the output-oriented Malmquist TFP, though there are some minor differences. [2]This suggests that different prices and value shares used as the weights are determining the differences in TFP measure between using the superlative index and the quantity-only based index.

[2] The related results obtained from the robusteness check are available upon request from authors.

5 Conclusions

International comparison of agricultural productivity has become one of the important issues for policymakers around the world. Yet, there are challenging issues both in the construction of cross-country consistent data as well as the choice of measurement methods. This paper first constructs a novel cross-country consistent dataset built upon production accounts at the commodity level for inputs and outputs for the estimation and comparison of agricultural TFP for Australia, Canada and the United States between 1961 and 2006. Using this cross-country consistent data, we estimate agricultural TFP across countries. We find that agricultural productivity in these three countries have generally been increasing during the period under study, though uneven across countries.

Second, we compare the performance of the two most widely adopted methods in cross-country productivity estimation, namely the superlative index method and the quantity-based index method. The quantity-only based index method has been widely used for measuring and comparing agricultural productivity growth across countries due to its advantage of requiring no priori price information. Yet, how well the method perform in providing reliable estimation of cross-country consistent agricultural TFP level and its growth is subject to debate. Our results suggest that TFP estimates obtained from using the superlative index outperforms those obtained from using the quantity-only based index. There are potentially two bias problems in the quantity-only based TFP index. One is that TFP estimates obtained from using the superlative index are more reliable relative to those obtained from using the quantity-only based index, and the other is that the superlative index TFP is more consistent in aggregation than the quantity-only based index TFP. Both problems are coming from the fact that the implicit prices of outputs and inputs (used by the quantity-only based index) could be significantly different from the market prices (used by the superlative index), rather than the choice of function form among others.

Our results suggest that the superlative TFP index method is still superior to the quantity-only based TFP index method in making international comparison of agricultural productivity. Our finding points to the importance of price data collection work for cross-country consistent agricultural productivity comparison.

Appendix A: Definition of Agricultural Production Accounts for the United States, Canada and Australia

Agricultural production account data are defined and collected consistently among the three countries, the United States, Canada and Australia. All data were collected on a calendar year basis. For Australia, this meant converting financial year data by taking a simple average of two consecutive financial years. We describe each variable in detail in this section.

Outputs

Output variables were collected under three categories: crops, livestock and other outputs. Crop outputs included grains and ensilage, oil seed, vegetables and melons, fruits and nuts. Livestock outputs included slaughter livestock (red meat), poultry and eggs, and other animal products (dairy and wool). Other outputs included 'non-separable secondary activities' such as income from machinery hire and contract services.

Primary agricultural outputs included deliveries to final demand as well as intermediate demand and on-farm use. Primary output is approximated by total sales plus non-market transactions (that is, cross-industry transfers through long-term contracts and on-farm use such as animal feed). Where production statistics are not directly available, primary output is approximated from changes in inventory for each commodity.

Outputs from non-separable secondary activities are defined as goods and services whose costs cannot be observed separately from those of primary agricultural outputs. Two types of secondary activities are included: on-farm production activities, such as the processing, packaging and marketing of agricultural products and services provision, such as machinery hire and land lease.

Government subsidies or taxes are included in agricultural outputs, since the value of inputs is inclusive of indirect taxes. However, the differences in government subsidies or taxes between countries may distort differences in total output.

Inputs

Input variables were collected under four categories: intermediate inputs, capital, land and labour. Capital and land inputs are estimated as service flows.

Intermediate inputs

Intermediate inputs comprise all materials and services consumed, excluding fixed capital, land and labour inputs. It includes 10 categories, namely: fuel, electricity, fertilisers and chemicals, fodder and seed, livestock purchases, water purchases, marketing services, repairs and maintenance, plant and machinery hire, and 'other materials and services'.

Fuel (including lubricants) and electricity are estimated from the total quantity consumed and the farmers' prices paid for petrol, off-road automobile diesel oil, liquefied natural gas and electricity. A fuel price index was calculated using quantity consumed for petrol, automobile diesel oil and liquefied natural gas as weights. The quantity of fuel consumed was obtained through dividing the expenditure by this fuel price. The price of electricity was estimated separately and used to deflate electricity expenditure for its quantity consumed as well.

Other intermediate inputs were estimated as implicit quantities. Price indexes were sourced domestically, except for pesticides and chemicals where quality-adjusted price data were sourced from the World Bank World Development Indicator database and FAO statistics. The quality-adjusted data were for 2005 and used with domestic time-series prices to impute a trend.

Consistent with the treatment of output, intermediate inputs were valued at farm-gate prices, including direct taxes and excluding indirect taxes and subsidies.

Capital

Following Ball et al. (2001 and 2010), three types of capital inputs are defined as non-dwelling buildings and structures, plant and machinery and transportation vehicles. While relevant, the inventory of crops, livestock and other biomass resources, such as vineyards and orchards, are not included because of inadequate value data. However, these capital inputs are likely to represent a relatively small proportion of total capital.

The measurement of capital input begins with using investments in constant prices to calculate capital stock of the three types of capital goods. At each time point t, the stock of capital K(t), is the sum of all past investments, $I_{t-\tau}$, weighted by the relative efficiencies of capital goods of each age τ , S_τ.

$$K_t = \sum_{\tau=0}^{\infty} S_\tau I_{t-\tau} \quad \text{(A1)}$$

Using equation (A1) to estimate capital stock, the efficiencies of capital goods have to be defined explicitly. Similar to Ball et al. (2010), two parameters including the service life of the asset, L, and a decay parameter, β, are used to specify the functional form, $S(.)$ such that

$$S(\tau) = (L - \tau)/(L - \beta\tau), \text{ if } 0 \le \tau \le L,$$

$$S(\tau) = 0, \text{ if } \tau > L \quad \text{(A2)}$$

Each type of capital asset has an assumed distribution of actual service life which provides some mean service life $\bar{L}$. In this analysis, the asset lives for non-dwelling buildings and structures, plant and machinery, and transport and other vehicles are assumed to be 40 years, 20 years and 15 years, respectively, with an assumed standard normal distribution truncated at points two standard deviations before and after the mean service life.

The decay parameter β can take values between 0 and 1, with $\beta = 1$ implying that the capital asset does not depreciate over its service life. Although there is little empirical evidence on appropriate values of β, it is still reasonable to assume that the efficiency of a capital asset declines smoothly over most of its service life. Following Ball et al. (2001), decay parameters are set to be 0.75 for non-dwelling buildings and structures and 0.5 for all other capital assets, which reflect the assumption that efficiency declines more quickly in the later years of service (Penson et al. 1987; Romain et al. 1987).

The aggregate efficiency function was constructed as a weighted sum of individual efficiency functions where the weights are the frequency of occurrence.

Assuming the sector invests when the present value of the net revenue generated by an additional unit of capital exceeds the purchase price of the asset, the farm sector will invest in capital stock formation until the output price P satisfies:

$$P * \frac{\partial Y}{\partial K} = rW_K + \sum_{t=1}^{\infty} W_K \frac{\partial R_t}{\partial K}(1 + r)^{-t} = c \quad \text{(A3)}$$

where c is the implicit rental price of capital, r is the real rate of return and W_K is the price of an additional unit of capital (or investment).

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

Let F denote the present value of the rate of capital depreciation on one unit of capital according to the mortality distribution m

$$F = \sum_{t-1}^{\infty} m_t(1+r)^{-t} \quad \text{(A4)}$$

where $m(\tau) = -[S(\tau) - S(\tau - 1)]$ for $\tau = 1, \dots, L$.

It can be shown that $\sum_{t=1}^{\infty} \frac{\partial R_t}{\partial K}(1+r)^{-t} = \sum_{t=1}^{\infty} F^t = \frac{F}{1-F}$ such that

$$c = \frac{rW_K}{1-F} \quad \text{(A5)}$$

Following Ball et al. (2010), the real rate of return r is approximated with an ex-ante rate, estimated as the nominal rate of return less capital gains. The nominal rate of return is obtained by using the endogenous approach with government bonds of all maturities. The choice of interest rate is widely debated. Andersen et al. (2011) argued that use of a fixed interest rate generates more plausible estimates of capital services in the United States than use of an annual market rate, while Jorgenson & Schreyer (2012) proposed to use the residual of output value deducting input costs for an endogenous real interest rate. To test the sensitivity of measured capital services to different real interest rates, both ex-ante and ex-post rates were estimated. The ex-ante rate was chosen for this study as it was found less volatile than the ex-post rate.

Land

The value of land service flows is given by the product of land stock and rental price. The stock of land was estimated by using the total land areas operated. The rental price of land was obtained using Equation (A5) with the assumption of zero depreciation, i.e. $c = rW_L$, where land price W_L came from a hedonic function.

Observed agricultural land prices can be affected by many factors unrelated to agricultural production, such as urbanisation pressures, distance to major cities and government land release policies. Also, spatial differences in land quality may prevent direct comparison of prices between regions and over time. To address these problems, comparable land price indexes for each country were constructed using hedonic regression methods.

In this paper, the hedonic price of land is a generalised linear function of its characteristics relevant to agricultural production and some control variables. The function uses the Box-Cox (1964) transformation to represent the dependent variable and each continuous independent variable:

$$W_L(\lambda_0) = \sum_n \alpha_n X_n(\lambda_n) + \sum_d \gamma_d D_d + \varepsilon \quad \text{(A6)}$$

where $W_L(\lambda_0)$, representing the price of land, is the Box-Cox transformation of real observations, when $W_L > 0$, that is

$$W_L(\lambda_0) = f(x) = \begin{cases} \frac{W_L^{\lambda_0}}{\lambda_0}, \lambda_0 \neq 0 \\ \ln W_L, \lambda_0 = 0 \end{cases} \quad \text{(A7)}$$

Similarly, $X_n(\lambda_n)$, a vector of land characteristics associated with agricultural production, is the Box-Cox transformation of the continuous quality variable X_n where

$$X_n(\lambda_n) = f(x) = \begin{cases} (X_n^{\lambda_n} - 1)/\lambda_n, \lambda_n \neq 0 \\ \ln X_n, \lambda_n = 0 \end{cases} \qquad \text{(A8)}$$

and D is a vector of country dummies used to control for external factors. For simplicity, it is approximated with a group of region and time dummy variables and not subject to transformation; λ, α and γ are unknown parameter vectors to be determined in the regression and ε is a stochastic disturbance term. This expression can assume linear, logarithmic and intermediate nonlinear functional forms depending on the transformational parameter.

To employ the hedonic model, regional land prices and land characteristics were observed for each country in 2005. Land characteristic data for 2005 were sourced from the USDA World Soil Resources Office and selected following Eswaran et al. (2003) and Sanchez et al. (2003). GIS mapping was used to overlay country and regional boundaries with land characteristics data according to particular soil categories, including soil acidity, salinity, and moisture stress. The three countries use more than 18 common variables to capture environmental attributes.

Two additional attributes affecting the price of agricultural land should be considered: irrigation and population accessibility. Irrigation (the percentage of cropland irrigated) was included as a separate indicator of production capacity in water-stressed areas, as well as an interaction term between irrigation and soil acidity. A population accessibility index could be used to control for the impact of urbanisation and economic development on land prices; however, it was not included in this analysis due to data constraints. Such indexes have been constructed in previous literature by using a gravity model of urban development, and provided a measure of accessibility to population concentrations (Shi et al. 1997).

Labour

Labour is defined as total hours worked by hired, self-employed and unpaid family workers. Because data were only available on agricultural employment, total hours worked was imputed by multiplying the number of workers by the average hours worked per week and the number of weeks. For consistency, we use 52 weeks a year for this imputation.

Wages were not used to estimate the value share of labour inputs. This is because hourly wages do not capture total compensation to farm workers given the likelihood that additional employee benefits (such as lodging and superannuation contributions) were not included in wage statistics. In addition, compensation to self-employed workers is not directly observable.

Instead, the real cost of total labour use was derived using the accounting assumption that the value of total output equals the value of total input. This enabled real wages to be estimated as the real labour compensation (or total output value minus capital, land and intermediate input costs) divided by the total hours worked.

Finally, hired, self-employed and unpaid family workers were distinguished and their different prices due to education levels and work experience were used to adjust for labour quality in all three countries.

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