The Long-Run Relationship between Population and Average Living Standards in Australia

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Abstract: There is little argument that population growth has contributed to 'extensive' economic growth in Australia. There is less agreement on its contribution to 'intensive' growth, that is, growth in real income per capita, a proxy for average living standards. Economic historians and public policy analysts have traditionally approached this question in a neo-classical growth accounting framework. However, the role given to population in standard neo-classical and some endogenous growth models is arguably too restricted. If there is a systematic relationship between population and average living standards under a modern growth regime, it should be possible to recover this relationship in a vector autoregression (VAR) or vector error correction (VEC) framework. Toda and Yamamoto's (1995) approach to inference in VARs with non-stationary variables is used to relate the level of the population to real GDP per capita in Australia from 1820-2008 alongside open economy conditional convergence dynamics. The level of real GDP per capita is found to Granger cause population. By contrast, population has little predictive power for per capita income. Imposing a recursive identification scheme finds that population responds positively to shocks to real GDP per capita. The response of real GDP per capita to population shocks is more variable, but positive for 1945-2008. Applying a VEC framework allows us to better distinguish between short and long-run dynamics. From 1945-2008, there is bilateral long-run causality between per capita income and population, although confidence is greater that it is population that adjusts to any disequilibrium in the long-run relationship. Both the VAR and VEC specifications for 1945-2008 suggest that the level of the population has a small positive long-run effect on the level of real GDP per capita. These findings are at odds with the more frequently found view among Australian economic historians and public policy analysts that population growth and net migration subtract from average living standards.

Version: 29 March 2012

JEL Classification: O11, O56; N17

Keywords: Australia; population; immigration; economic growth; vector error correction.

1. Introduction

The long-run relationship between population growth and average living standards in Australia is viewed ambiguously by economic historians and economists. There is little argument that population growth and net migration have contributed to 'extensive' economic growth, ie the size of the Australian economy. There is less agreement on their contribution to 'intensive' growth, that is, growth in real national income per capita, a widely used proxy for average living standards.

Economists have generally approached this question in a growth accounting framework based on standard neo-classical growth models and assumptions. The contribution population makes to real output in these models is via the size of the working age population, the labour force and hours worked, augmented by technology and human and physical capital. Improvements in productivity are the main driver of economic growth and average living standards in the long-run.[1] Neo-classical growth models with constant returns to scale imply that growth in the labour force yields only transitory effects on the level of output and is thus broadly neutral for long-run growth in output per worker. However, population growth can also subtract from economic growth and living standards to the extent that it leads to a reduction in capital per worker and thus lower productivity.[2] There is no necessary connection between population growth and capital accumulation or technology in these models. The empirical cross-country growth regression literature exemplified by Mankiw, Romer and Weil[3] has typically found negative, though modest, effects on the level and growth rate of national income from population growth. This effect is usually mediated through the steady-state capital-labour ratio and/or changes in labour force participation rates.

Endogenous growth theory implies that population growth may drive technical change, although this literature is divided on whether the relationship between population and productivity is positive or negative. Jones[4] maintains that US and world growth is driven by research effort that is proportional to population. Romer[5] shows that 'an increase in the labour force can reduce the rate of technological change' because labour scarcity drives innovation. The implications of Romer's model find historical support in Habakkuk's[6] study of the US and the UK in the 19th century.

However, an alternative stream in the endogenous growth tradition maintains that population growth results in more generalised non-labour scarcities and short-run pecuniary externalties that in turn drive long-run technical change. In this tradition, the transmission mechanism from population growth to technical change is much broader and more mundane than the research and development (R&D) and human capital accumulation channels that have been the usual focus of the endogenous growth literature. The contribution of population growth to knowledge growth is difficult to measure and model and has traditionally been neglected in favour of more tractable models and relationships. However, Simon,[7] Simon and Kuran[8], Kuznets,[9] and Boserup [10] have nonetheless shown a positive long-run relationship between

[1] Jones, *Introduction to Economic Growth*.
[2] Weil, *Economic Growth*, 99.
[3] "A Contribution to the Empirics of Economic Growth."
[4] "Sources of U.S. Economic Growth in a World of Ideas."
[5] "Capital, Labor, and Productivity," 337.
[6] *American and British Technology in the Nineteenth Century; the Search for Labour-saving Inventions.*
[7] *Theory of Population and Economic Growth.*
[8] *The Great Breakthrough and Its Cause.*
[9] *Population Capital and Growth.*

population growth, population density, innovation and technological change. This perspective is not unrelated to the observation observation that real commodity prices tend to decline in the long-run.[11] Population growth has also been given a role in the transition from Malthusian to modern economic growth, as well as the dynamics of modern economic growth that are more relevant to Australia.[12] This stream of endogenous growth theory suggests the possibility of a positive long-run relationship between population and the level of real GDP per capita that is at odds with the implications of standard neo-classical growth models and the empirical cross-country growth regression literature.

The relationship between population and real GDP per capita can be considered in a long-run dynamic setting using time series methods, rather than in a growth accounting or static cross-country regression framework. In addition to capturing long-run dynamics, this approach does not depend on the assumptions of a particular model of economic growth, although it can be used to test the implications of different models. It allows for broader transmission mechanisms from population to real GDP per capita, even if these transmission mechanisms are not specifically modelled. It can also shed light on the causal direction of these relationships.

Section 2 briefly reviews some relevant contributions by economic historians, as well as studies of the more contemporary and prospective relationship between population growth, net migration and real GDP per capita in Australia. For the most part, the literature suggests that population and net migration subtract from average living standards, although without always distinguishing between short and long-run. The limitations of this literature are discussed, particularly the very restricted role given to population in these models.

Section 3 proposes an alternative vector autoregression (VAR) and vector error correction (VEC) framework for examining the relationship between Australian population growth and real GDP per capita alongside open economy and conditional convergence dynamics. The choice of variables to include in these models and the sample period are also motivated. These choices reflect data availability as well as Simon's view that the relationship between population and average living standards is best considered 'in the *very* long run' (emphasis in original).[13] According to Simon, the implications of population growth for average living standards are not fully apparent in periods under a quarter of a century. The long-run relationship of interest may therefore be observable only over very long periods within the modern (ie, post-Malthusian) growth regime. While shorter sample periods can be considered as a robustness check on the estimated long-run relationship, these shorter samples may be insufficient to capture the long-run relationship of interest. The estimated models in this paper cover the period from around 1822 to 2008, capturing most of Australia's history since European settlement in 1788, which coincides with modern economic growth.

Section 4 estimates the VAR and VEC models proposed in section 3. The level of real GDP per capita is found to Granger cause population, but population is found to have little predictive power for real GDP per capita. Imposing a recursive identification scheme on the VAR specifications finds that population responds positively to shocks to real GDP per capita. The response of real GDP per capita to population shocks is more variable across different specifications, but positive for the post-World War Two period. Conditioning on

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[10] *Population and Technology*.
[11] Barnett and Morse, *Scarcity and Growth*; Simon, *The Ultimate Resource 2*.
[12] Galor, *Unified Growth Theory*; Simon and Kuran, *The Great Breakthrough and Its Cause*.
[13] Simon, *The Economic Consequences of Immigration*, 197.

cointegrating relationships and applying a VEC framework enables us to better distinguish between short and long-run dynamics. For the post-World War Two period, real GDP per capita is found to Granger cause population in both the short and the long-run, however, there is also some support for long-run bilateral causality. The level of the population is found to have a small positive long-run effect on the level of real GDP per capita between 1945 and 2008, consistent with the VAR results. These findings are at odds with the more frequently found view among Australian economic historians and economists that population growth and net migration subtract from average living standards.

Section 5 concludes by noting some of the implications of these results and makes suggestions for further research.

2. Population, net migration and real GDP per capita in Australian economic history and public policy

Students of Australian economic history have for the most part neglected the long-run relationship between population and the level of per capita income. Most of the interest in demography on the part of economic historians has been confined to the implications of immigration and the age structure of the population for the business cycle and the expenditure composition of economic growth rather than the determination of per capita income over time.[14] Pope is notable in examining the relationship between population growth and per capita income for the period 1900-30.[15] Adopting standard neo-classical assumptions, Pope argued that since growth in net migration exceeded capital accumulation, immigration had likely lowered Australia's stock of capital per worker and productivity, expanding real GDP, but reducing real GDP per capita. Pope blamed Australia's historically poor per capita economic growth on immigration, arguing that Australia traded-off living standards against a bigger population to satisfy the 'populate or perish' imperative. This view has support from other economic historians. Kuznets, although sympathetic to the view that population growth has positive implications for long-run improvements in living standards, also thought that a low capital-labour ratio was implicated in Australia's relatively low per capita GDP growth between the 1860s and the early post-World War II period.[16] Gruen's Shann Memorial Lecture maintained that 'our high population growth rate...has exercised a negative effect on the improvement in our average living standards.' [17] Jolley reached a similar conclusion in relation to immigration.[18]

The implications of population growth and net migration for per capita income has often been considered in the context of contemporary policy debates, particularly in relation to the economic implications of population aging. While not strictly historical in focus, this modelling is often informed by historical data and calibrated on the basis of historical relationships. In contrast to demographers like McDonald,[19] Guest and McDonald[20]argue that a decrease in fertility could lead to a modest improvement in future living standards in

[14] Kelley, "Demographic Change and Economic Growth: Australia 1861-1911"; Withers, "Immigration and Economic Flutuations: An Application to the Late 19th Century"; Hall, "Some Long Period Effects of the Kinked Age Distribution of the Population of Australia 1861–1961."
[15] "Population and Australian Economic Development, 1900-1930."
[16] *Modern Economic Growth*, 67 and 79.
[17] "How Bad Is Australia's Economic Performance and Why?".
[18] "Immigration and Australia's Post-war Economic Growth."
[19] "The Shape of an Australian Population Policy."
[20] "Would a Decrease in Fertility Be a Threat to Living Standards in Australia?".

Australia. Their conclusions are specific to their simulation model, which adopts standard neo-classical assumptions, including constant returns to scale and exogenous technology. The modest improvement in living standards arises from the reduction in investment needed to maintain the capital-labour ratio and the simulation's implication that future increases in taxes due to an ageing population will have only a very small negative impact on future labour supply.

McDonald and Temple[21] present 'a partial analysis of the impact of migration on Australia.' The results are obtained by running the federal Treasury's Intergenerational Report (IGR) demographic projections through the Productivity Commission's demographic model. While not an economic model, their conclusions are consistent with standard models and the Treasury's IGR projections in arguing that 'the impacts of migration upon the rate of growth of GDP per capita derive from the impact of migration upon the proportion of the population that are in the labour force which, in turn, is determined largely by the extent of population aging.' Immigration boosts real GDP per capita, but only by increasing hours worked due to a slowing in population aging. This conclusion is characteristic of models that limit the contribution of population growth and immigration to hours worked. Although immigration is widely thought to have had little or no impact on the age structure of the population historically, McDonald and Temple argue it may have some impact in the future.

A Productivity Commission report *Economic Impacts of Migration and Population Growth* concluded that 'migration has relatively small but generally benign economic effects.'[22] The modelling for the Commission also assumed that immigration subtracts from labour productivity due to a decrease in the capital-labour ratio. As the Commission readily concedes, it is inherently difficult to quantify and model factors such as the gains from trade and increased competition, much less the role of innovation, so these considerations are omitted from the modelling. The Commission's 2006 modelling and conclusions do not differ substantially from the major Australian studies into the economic implications of immigration conducted in the 1970s and 1980s, including economic modelling for the 1988 Fitzgerald Committee of inquiry. Fitzgerald concluded that 'the positive effects of immigration on the economy are necessarily limited. They can account for only a fraction of total economic growth.'[23]

A common theme running through this literature is the very restricted role given to population and net migration in driving growth in real GDP and real GDP per capita. This role is usually confined to the contribution of labour inputs (e.g. hours worked) and the role of the capital-labour ratio in driving productivity. There are some exceptions to this approach found in the literature. Nevile[24] argues that population growth leads to improved productivity growth through the 'Salter effect,' named after the work of Australian economist Wilfred Salter.[25] In contrast to Romer,[26] Salter maintained that faster population growth gives rise to a more modern and productive capital stock. Nevile's approach is otherwise conventional in maintaining that the Salter effect must compete with the role of immigration in diluting the capital-labour ratio and productivity.

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[21] *Immigration, Labour Supply and Per Capita Gross Domestic Product. Australia 2010-2050: Final Report*.
[22] *Economic Impacts of Migration and Population Growth*, 161.
[23] *Immigration, a Commitment to Australia: The Report of the Committee to Advise on Australia's Immigration Policies*, 37.
[24] *The Effect of Immigration on Australian Living Standards*.
[25] *Productivity and Technical Change*.
[26] "Capital, Labor, and Productivity."

3. An alternative VAR and VEC approach

VAR and VEC modelling are well-suited to examining the long-run implications of population growth for the level of real GDP per capita under a modern (ie, post-Malthusian) growth regime). These models have the advantage of being relatively atheoretical and do not depend on the imposition of assumptions from a particular model of economic growth, while still providing an indirect test of some of the implications of candidate growth models. These models also have the advantage of being parsimonious. The stochastic trends embedded in the model can effectively capture many of the exogenous determinants of the variables, allowing the researcher to focus on the relationship between a small number of variables of interest.

While the VAR and VEC approach is relatively atheoretical, the choice of variables to include in any model still needs careful motivation. The main relationship of interest is that between Australia's population (*p* subsequently) and real GDP per capita (*ypc*) (see Appendix 1 for data definitions and sources). Population could be expected to contribute directly to growth in real GDP via hours worked and make indirect contributions through economies of scale and as a driver of endogenous technical change. At the same time, population growth may also dilute the stock of capital per worker, lowering productivity and subtract from measured living standards directly through the denominator of the identity for real GDP per capita. In principle, it should be possible to recover any systematic relationship between population and real GDP per capita in a bivariate setting.

Apart from population, we can consider a number of other potential determinants of long-run average living standards in Australia. As a small open economy integrated into the Anglo-American economies, Australian real GDP per capita can also be expected to have a long-run relationship with real GDP per capita in the United Kingdom. Australia shares with the UK a common history and institutional arrangements as well as close trade and capital market linkages. Australia has historically been a net importer of foreign capital and technology[27] and its standard of living is largely determined by its openness to these influences along with its institutional inheritance. Greasley and Oxley[28] show that 'the British and Australian economies moved closely together throughout the period 1870 to 1992, with no significant trend in their comparative economic performance... Australia and Britain attain long-run income convergence.' Greasley and Oxley's[29] tests of the conditional convergence hypothesis show there is a long-run relationship between Australian, UK and US real GDP per capita, but the relationship between Australia and the UK stands out among the Anglo-American economies as the closest. As Greasley and Oxley[30] note, a sufficient condition for convergence would imply both stochastic and deterministic cointegration between Australian and foreign income per capita. Conditional convergence also implies that output innovations are transmitted internationally. The bivariate model relating population and real GDP per capita can be augmented with purchasing power parity-adjusted real GDP per capita for the UK (ypc_{UK}) to capture these long-run open economy and convergence dynamics.

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[27] Butlin, *Investment in Australian Economic Development, 1861-1900*.
[28] "A Tale of Two Dominions," 312–13.
[29] "A Time Series Perspective on Convergence."
[30] Ibid.

Neo-classical growth models assign a role to capital accumulation as well as labour in driving growth in real GDP per capita, although both take a back-seat to productivity in the long-run. The stock of capital per worker and the capital-output ratio are widely considered to be important determinants of differences in real GDP per capita over time and across countries. However, consistent measures for these variables are limited to the period since 1960. The autoregressive component of Australian real GDP per capita as well as the open economy relationships in the model could be expected to capture some of the dynamics of domestic capital accumulation. It would also be desirable to identify a distinct role for net migration in the model. However, the migration data for Australia are subject to numerous methodological breaks and do not clearly distinguish between permanent and temporary migration, rendering the contribution of migration flows to the stock of the population ambiguous.[31] We therefore limit our consideration of the data to the bivariate relationship between population and real GDP per capita, which is then augmented with a trivariate model including UK real per capita to capture open economy and convergence dynamics.

The time series properties of the data are considered in Appendix 2, with Phillips-Perron and KPSS tests for the order of integration of the variables. Variables are found to be I(1) in levels and stationary in first differences, regardless of choice of exogenous regressors. The data are thus suitable for investigation via Toda and Yamamoto's[32] procedure for inference in VARs where the levels of the variables may be integrated or cointegrated of arbitrary order. Lag length k is chosen via the usual model selection criteria. A $p = (k + d_{max})$-order VAR is then estimated where d_{max} is the maximal order of integration we suspect in the data. Based on the order of integration tests in Appendix 2, d_{max} is set equal to 1. Restrictions on the first k coefficient matrices can then be tested with the last d_{max} lagged vectors in the model ignored using standard asymptotic theory without the biases introduced by pre-tests for order of integration and cointegration. These pre-test biases render invalid the Wald and likelihood ratio tests that might otherwise be employed in a VEC framework. We can still test for cointegration among the variables and estimate a VEC model in order to better distinguish between short and long-run dynamics and as a check on the VAR results, but pre-test bias limits our ability to test restrictions on VEC coefficients.

A kth-order VAR in levels of the variables can be estimated based on the following form:

$$y_t = a_0 d_t + \sum_{i=1}^{k-1} \Gamma y_{t-i} + \varepsilon_t \qquad (1)$$

where y_t is an n x 1 vector of endogenous variables in logarithms, d_t is a vector of deterministic elements, Γ_i are the matrices of the dynamic coefficients and ε_t is a vector of random errors with an expected value of zero. Equation (1) can be used to test for lag order and autocorrelation. A recursive identification scheme can then be imposed to generate impulse response functions to orthogonalise shocks to the endogenous variables.

Following Toda and Yamamoto, a $p = (k + d_{max})$-order VAR in levels of the variables can also be estimated based on the following form:

$$y_t = a_0 d_t + \sum_{i=1}^{p-1} \Gamma y_{t-i} + \varepsilon_t \qquad (2)$$

[31] Phillips, Klapdor, and Simon-Davies, *Migration to Australia Since Federation: a Guide to the Statistics*.
[32] Toda and Yamamoto, "Statistical Inference in Vector Autoregressions with Possibly Integrated Processes."

Restrictions on the dynamic coefficients can then be tested using standard asymptotic theory by treating the last lag (d_{max}) as exogenous.

Based on the outcome of cointegration tests, a VEC model of the following form can also be estimated to better distinguish between short and long-run dynamics:

$$\Delta y_t = \alpha(\beta y_{t-1}) + \sum_{i=1}^{k-1} \Gamma \Delta y_{t-i} + \varepsilon_t \qquad (3)$$

where Δy_t contains the growth rates of the variables in logarithms, α is a matrix of adjustment coefficients, β is the matrix of cointegrating vectors, Γ_i are the matrices of short-run dynamic coefficients, and ε_t is a vector of random errors. The α matrix and short-run coefficients allow us to distinguish between short and long-run dynamics, while the β matrix allows us to quantify long-run relationships.

The bivariate relationship between the log level of *p* and *ypc* can be estimated using specification (1) including a constant term. In order to estimate the long-run relationship, we use the longest sample period possible. The model is estimated for the period 1822-2008 and for the sub-samples 1822-1945 and 1945-2008. The starting point reflects the beginning of regular annual observations on Australian GDP per capita in the Maddison data adjusted for the lag order of the VAR. This covers most of Australia's history since European settlement in 1788. The trivariate relationship between *p*, *ypc* and ypc_{uk} can be similarly estimated from 1832 and for pre- and post-1945 sub-samples. The later starting point reflects the later start for regular annual observations on UK GDP per capita in the Maddison data and adjusted for the lag order of the VAR. Conditional on cointegration, we then estimate (3) for the bivariate and trivariate case over the same sample periods.

4. Results

4.1 Granger Non-Causality Tests

Specification (2) is used to test for Granger non-causality between the variables based on the Toda and Yamamoto procedure outlined above.

Table 1: Wald tests for Granger non-causality

Bivariate VAR (p, ypc)

Sample	**VAR(k, d_{max})**	**p-values for H_0 of Granger non-causality**	
		$p \rightarrow ypc$	**$ypc \rightarrow p$**
1822-2008	2,1	0.06	0.00
1822-1945	2,1	0.40	0.00
1945-2008	3,1	0.64	0.00

Trivariate VAR (p, ypc, ypc_{uk})

Sample	**VAR(k, d_{max})**	**p-values for H_0 of Granger non-causality**	
		$p \rightarrow ypc$	**$ypc \rightarrow p$**
1832-2008	2,1	0.66	0.00
1832-1945	2,1	0.63	0.00
1945-2008	3,1	0.64	0.00
		$ypc_{uk} \rightarrow ypc$	**$ypc \rightarrow ypc_{uk}$**
1832-2008	2,1	0.03	0.30
1832-1945	2,1	0.23	0.43
1945-2008	3,1	0.36	0.23
		$p \rightarrow ypc_{uk}$	**$ypc_{uk} \rightarrow p$**
1832-2008	2,1	0.67	0.26
1832-1945	2,1	0.58	0.39
1945-2008	3,1	0.08	0.75

The Granger non-causality tests based on both bivariate and trivariate models imply that real GDP per capita predicts population. Population does not predict average living standards, although in the bivariate case we only narrowly accept non-causality from population to living standards for the sample period as a whole. We also only narrowly accept Granger non-causality running from Australian population to UK real GDP per capita for the post-war period. A possible explanation for this relationship is that migration flows from the UK to Australia anticipate developments in the UK economy.

4.2 Impulse Response Analysis

A recursive identification scheme is imposed to generate impulse response functions (IRFs) that can identify and quantify causal relationships. The data are ordered from most to least exogenous. In the bivariate model, *ypc* is ordered before *p*, which is consistent with the implications of the Granger non-causality tests in Table 1. In the trivariate model, ypc_{uk} is ordered first, followed by *ypc* and then *p*. UK real GDP per capita can be considered to be exogenous for Australian living standards and population, although the Australian data may have some predictive power for the UK data (if, for example, the Australian business cycle leads the UK business cycle). Australian per capita income and population have no contemporaneous effect on UK per capita income, while Australian population has no contemporaneous effect on Australian per capita income based on this ordering. While the IRFs are in-principle sensitive to the recursive ordering, changing the order did not lead to substantially different results. Consistent with Simon's focus on the very long-run relationship, impulse response functions are generated for 100 years, with asymptotic error bands. The results are shown in Appendix 3.

In the bivariate case (Figures 1-3), real GDP per capita shows a negative response to population shocks for the period 1822-2008 and 1822-1945 (Figures 1 and 2), although the standard error bands suggest this response may not be different from zero. For the 1945-2008 period (Figure 3), real GDP per capita responds positively to population shocks, with the response peaking around 0.7% after around 10 years. The non-zero response implies some bilateral causality between population and per capita income in the post-World War Two period. Population responds positively to shocks to real GDP per capita, although the response for the 1945-2008 period (Figure 3) is smaller and the standard error bands suggest we should not be confident that there is still a positive response after five years. While positive shocks to real GDP per capita could be expected to slow population growth rates through income effects on fertility rates, positive shocks to the level of income could also increase longevity rates and be expected to attract net inbound migration. These results are consistent with the Granger non-causality tests in suggesting that per capita income predicts population not the other way around, with the possible exception of the 1945-2008.

In the trivariate model (Figures 4-6), population shocks have no effect on real GDP per capita for the full 1832-2008 sample (Figure 4) and the 1832-1945 sub-sample (Figure 5). However, there is a positive response for the post-1945 sample that peaks at about 0.6% after 15 years, similar to the bivariate results. This again suggests some bilateral causality between population and real GDP per capita from 1945 onwards. The response of real GDP per capita to population shocks is similar to that for the bivariate case.

The other responses in the trivariate model are mostly consistent with expectations. Australian real GDP per capita responds positively to shocks to UK real GDP per capita. Shocks to Australian GDP per capita and population have no effect on UK real GDP per capita or are at least difficult to distinguish from zero based on the standard error bands. The only puzzle is the apparent positive response of Australian population to shocks to UK real GDP per capita, although subject to wide standard error bands (this was also suggested by the very narrow acceptance of Granger non-causality between UK income per capita and Australian population in Table 1 for the 1945-2008 period). As noted previously, this could reflect the impact of economic shocks in the UK driving migration flows to Australia, which would be significant for Australian population growth.

4.3 Cointegration Analysis

Respecifying the VARs as VEC models has the potential to better distinguish between short and long-run dynamics, conditional on tests for cointegration. However, inference derived from restrictions on VEC coefficients will be subject to the pre-test biases already discussed. Johansen and Juselius[33] procedure tests for cointegrating relationships between the variables of interest are conducted. Where cointegrating relationships are identified, a VEC model normalised on real GDP per capita is used to estimate the long-run relationships with population and UK real GDP per capita. The direction of long-run causality can also be identified, subject to the limitations on inference due to potential pre-test bias.

The Pantula[34] principle is applied, testing down from the most restricted to the least restricted VEC model until a rank order is accepted. For each model and sample period, rank order was

[33] "Maximum Likelihood Estimation and Inference on Cointegration — with Applications to the Demand for Money."
[34] Pantula, "Testing for Unit Roots in Time Series Data."

established using the most restricted model (equation (3) above), so Johansen and Juselius procedure tests are shown based only on this specification, with a lag order of 1 established by SIC. Results are shown in Appendix 4.

The test statistics imply a single cointegrating relationship between population and real GDP per capita for the full sample and for the 1945-2008 period. Unfortunately, more than one cointegrating relationship is suggested for the period 1823-1945, which is obviously problematic for a two variable model. In the three variable case, a single cointegrating relationship is identified for the full sample, although we only narrowly accept at most one cointegrating relationship. The pre-1945 sample suggests two cointegrating relationships based on the trace test and one relationship on the maximum eigenvalue test, but *p*-values are low in any event. A single cointegrating relationship between the three variables is more robustly identified for the 1945-2008 period. These results suggest that to the extent that there is a cointegrating relationship, it is only robust for the trivariate model in the 1945-2008 period.

A VEC model for the trivariate case can be estimated based on equation (3) for 1945-2008. The long-run relationships normalised on *ypc* are as follows (standard errors in parentheses and *t*-statistics in brackets):

$$ypc = \underset{\substack{(0.056)\\ [3.792]}}{0.212}p + \underset{\substack{(0.094)\\ [7.057]}}{0.666}ypc_{uk}$$

The level of the population is found to have a positive and statistically significant long-run effect on the level of Australian real GDP per capita over the post-1945 period, although the elasticity is small at 0.2%. The elasticity of Australian to UK real GDP per capita is around 0.7%.

The estimated adjustment coefficients weighting the cointegration vectors measure the feedback effect of the lagged disequilibrium in the vector autoregression. Table 2 reports the estimated adjustment coefficients for each dependent variable, along with the short-run VAR coefficients and coefficient of determination for each equation in the VAR.

Table 2: Estimated adjustment and short-run dynamic coefficients

	Δypc	Δp	Δypc_{UK}
α_{t-1}	-0.063	-0.030	0.006
	(0.027)	(0.005)	(0.026)
	[-2.346]	[-5.507]	[-0.239]
Δypc_{t-1}	0.407	0.078	0.315
	(0.136)	(0.027)	(0.130)
	[2.979]	[2.861]	[2.420]
Δp_{t-1}	-0.595	0.405	0.282
	(0.485)	(0.098)	(0.463)
	[-1.227]	[4.148]	[0.608]
Δypc_{ukt-1}	0.211	0.006	0.303
	(0.134)	(0.027)	(0.128)
	[1.571]	[0.203]	[2.365]
Adj.R^2	0.226	0.606	0.270

Notes: Based on $\Delta y_t = \alpha(\beta y_{t-1}) + \sum_{i=1}^{k-1} \Gamma \, \Delta y_{t-i} + \varepsilon_t$. Sample period 1945-2008. Standard errors in parentheses and *t*-statistics in brackets.

The adjustment coefficients imply disequilibrium in the long-run relationship feeds back on to Australian real GDP per capita and population, but not on to UK real GDP per capita, consistent with the latter being exogenous. The adjustment to long-run equilibrium is slow, but twice as fast for per capita income as for population, consistent with greater inertia in population than real GDP per capita. These results imply long-run bilateral causality between the level of the population and Australian real GDP per capita from 1945-2008, although there is greater confidence that it is population rather than income that adjusts to any disequilibrium in the long-run relationship.

The short-run dynamics suggest that the lagged growth rate of the population subtracts from real GDP per capita growth, but subject to a large standard error. Lagged growth in real GDP per capita has a small short-run effect on the growth rate of the population that is statistically more robust. Lagged Australian real GDP per capita has a positive effect on growth in UK real GDP per capita. This is likely due to the Australian business cycle having a leading relationship with the UK business cycle.

While the VEC framework requires more conditioning information and is statistically more demanding, it is also potentially more informative. The lack of robust evidence for cointegrating relationships before 1945 could be symptomatic of both data issues and the significant shocks in the pre-1945 period (the depressions of the 1890s and the 1930s and two world wars). However, the VEC results for the 1945-2008 period are more robust and consistent with those obtained using the VAR approach.

5. Conclusion

Economic historians and those modelling the more contemporary and prospective relationship between Australia's population and real GDP per capita have often maintained that population growth and net migration lower average living standards. These conclusions have been driven by conventional neo-classical growth models and assumptions that have relied on hours worked and the capital-labor ratio as the transmission mechanism from population and net migration to real GDP and measured average living standards. In the long-run, however, both capital and labour take a back-seat to productivity in driving real GDP per capita in standard growth accounting farmeworks. By contrast, at least one stream in the endogenous growth tradition implies a much more open-ended and long-run relationship between population and average living standards. This relationship is amenable to testing alongside open economy and conditional convergence dynamics using the time series framework employed here.

The Toda and Yamamoto procedure for inference in VARs with non-stationary variables and impulse response analysis both suggest that average living standards predict population, but population has little predictive power for average living standards between the early 19th century and 2008. The role of per capita income in driving population can be attributed to income effects on natural increase and net migration. There is, however, some evidence for shocks to population having a positive effect on GDP per capita between 1945 and 2008.

Conditioning on cointegrating relationships among the variables and applying a VEC framework, there is evidence for long-run bilateral causality between population and real GDP per capita between 1945 and 2008, although we are more confident that it is population and not per capita income that adjusts to any disequilibrium in the long-run relationship. The long-run elasticity of real GDP per capita to population is small at only 0.2% and small relative to the open economy and convergence dynamics captured by the long-run relationship with average living standards in the UK. In the short-run, the lagged growth rate of the population is not a statistically significant determinant of real GDP per capita growth, but lagged growth in per capita income has some explanatory power for the growth rate of the population. These findings are at odds with the more commonly held view among economic historians and public policy analysts that population subtracts from living standards, whether in the short or the long-run.

Further research could examine the implications of age dependency ratios for the relationship between population and real GDP per capita. It would also be desirable to distinguish between the implications of net migration and natural increase, subject to the measurement issues raised earlier. Patents could also be considered to incorporate an explicit innovation channel into the models.

The approach taken here could also be applied to other small open economies integrated with the world economy. New Zealand and Canada are potential candidates for this approach. However, among the Anglo-American economies, the relationship between Australian and UK real GDP per capita would seem to be uniquely close. Estimating the long-run relationship between population and per capita income alongside an open economy/convergence relationship may be less straightforward in the case of other small open economies.

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Appendix 1: Data Definitions and Sources

ypc and $\boldsymbol{ypc_{UK}}$ log of purchasing power parity-adjusted Australian and UK real GDP per capita, respectively. Source: Angus Maddison, Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD, http://www.ggdc.net/maddison/. Accessed 29 June 2010.

p log of population. Source: Angus Maddison, Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD, http://www.ggdc.net/maddison/. Accessed 29 June 2010.

Appendix 2: Order of integration tests

Phillips-Perron order of integration tests (unit root null)

Variable[(a)]	Lags	Constant	Lag	Constant & trend
Level				
p	1	-1.995	1	-0.762
ypc	1	-2.012	1	-2.714
ypc_{UK}	1	1.509	1	-0.590
First-difference				
Δp	1	-4.391***	1	-4.815***
Δypc	1	-14.311***	1	-14.406***
Δypc_{UK}	1	-9.236***	1	-9.463***

Notes: (a) *S*ample period 1821/1832-2008. Asterisks (***,**,*) denote statistical significance at the 1%, 5% and 10% levels, respectively.

KPSS order of integration tests (stationary null)

Variable[(a)]	Lags	Constant	Lag	Constant & trend
Level				
p	0	-1.607***	0	0.359***
ypc	0	-1.547***	0	-0.206**
ypc_{UK}	0	1.682***	0	0.324***
First-difference				
Δp	0	0.406	0	0.081
Δypc	0	0.307	0	0.185
Δypc_{UK}	0	0.331	0	0.127

Notes: (a) *S*ample period 1821/1832-2008. Asterisks (***,**,*) denote statistical significance at the 1%, 5% and 10% levels, respectively.

Appendix 3: Impulse Response Analysis

Figure 1: Recursive VAR(2) (*ypc, p*) 1822 to 2008

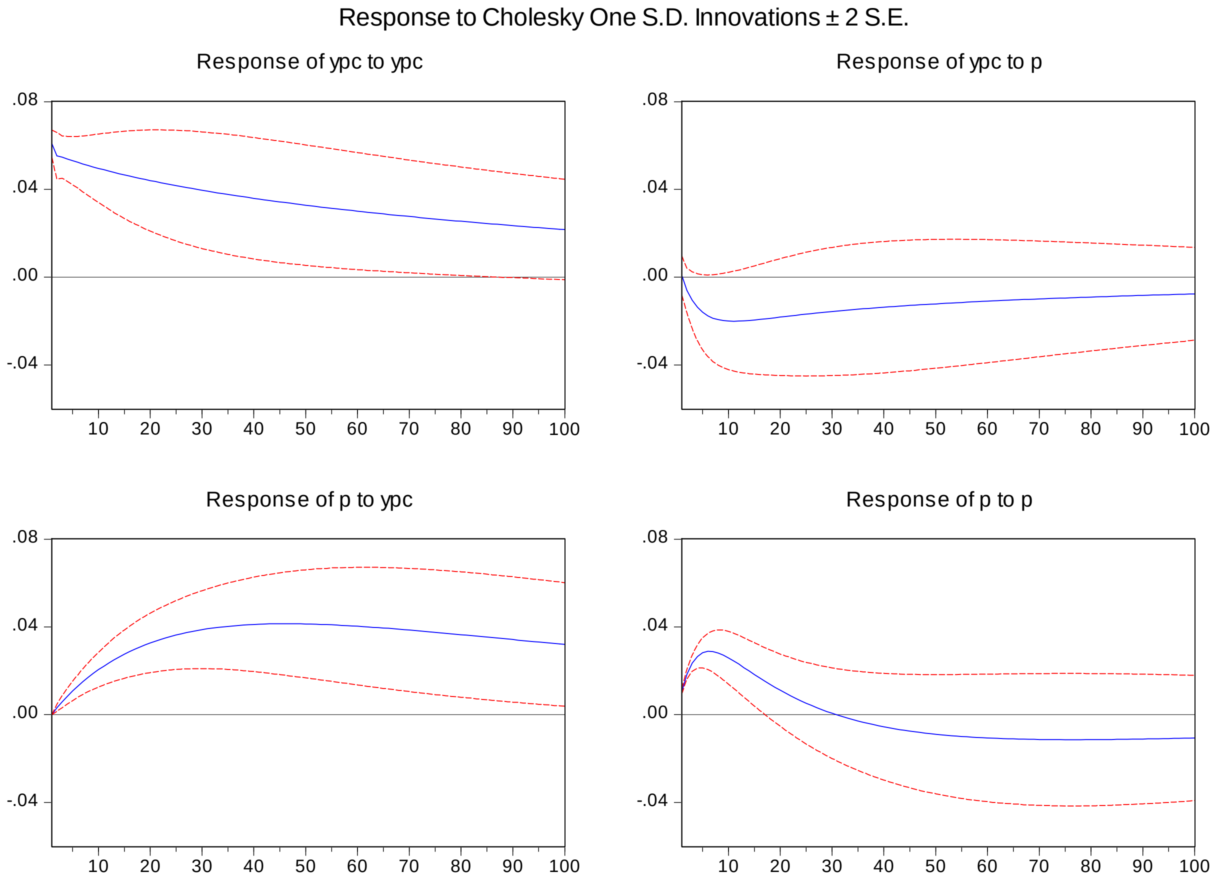


Figure 2: Recursive VAR(2) (*ypc, p*) 1822 to 1945

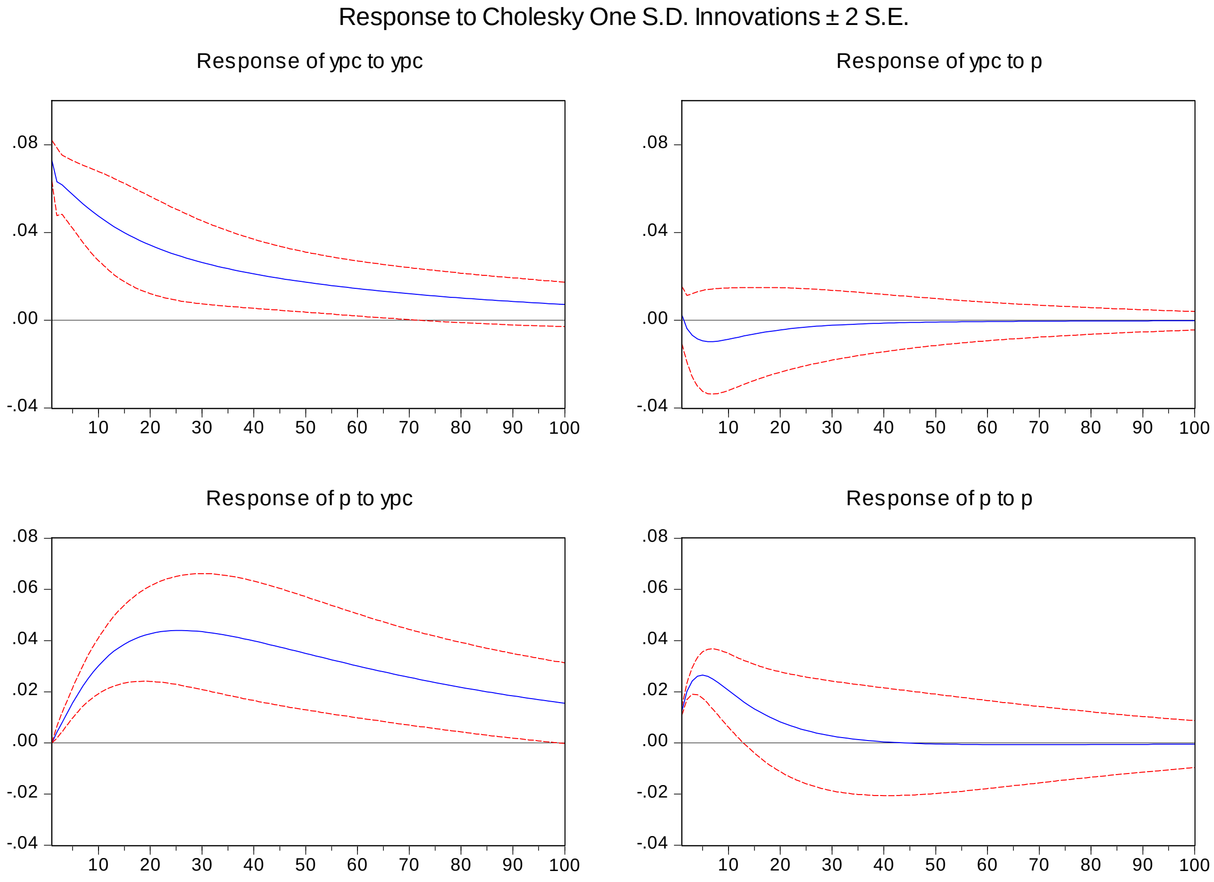


Figure 3: Recursive VAR(3) (*ypc*, *p*) 1945 to 2008

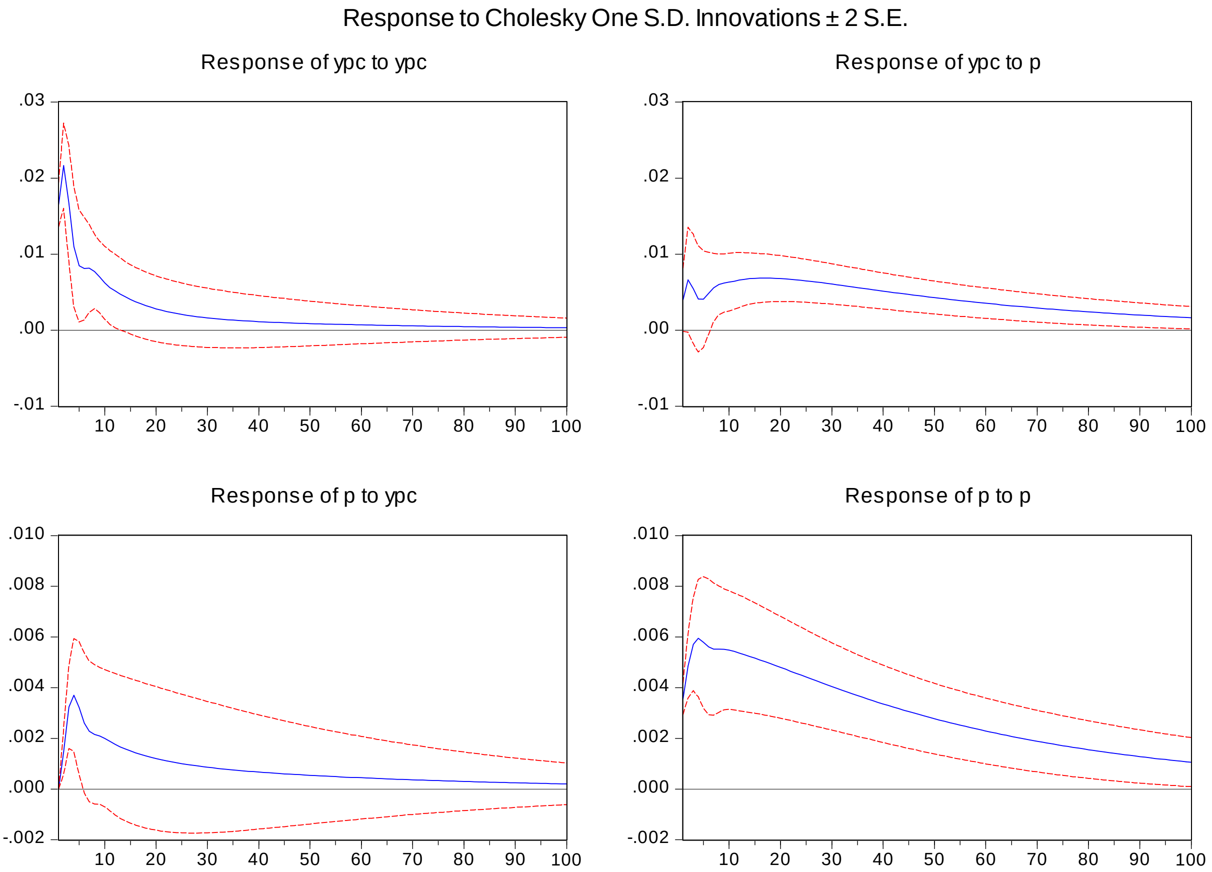


Figure 4: Recursive VAR(2) (ypc_{uk}, ypc, p) 1832 to 2008

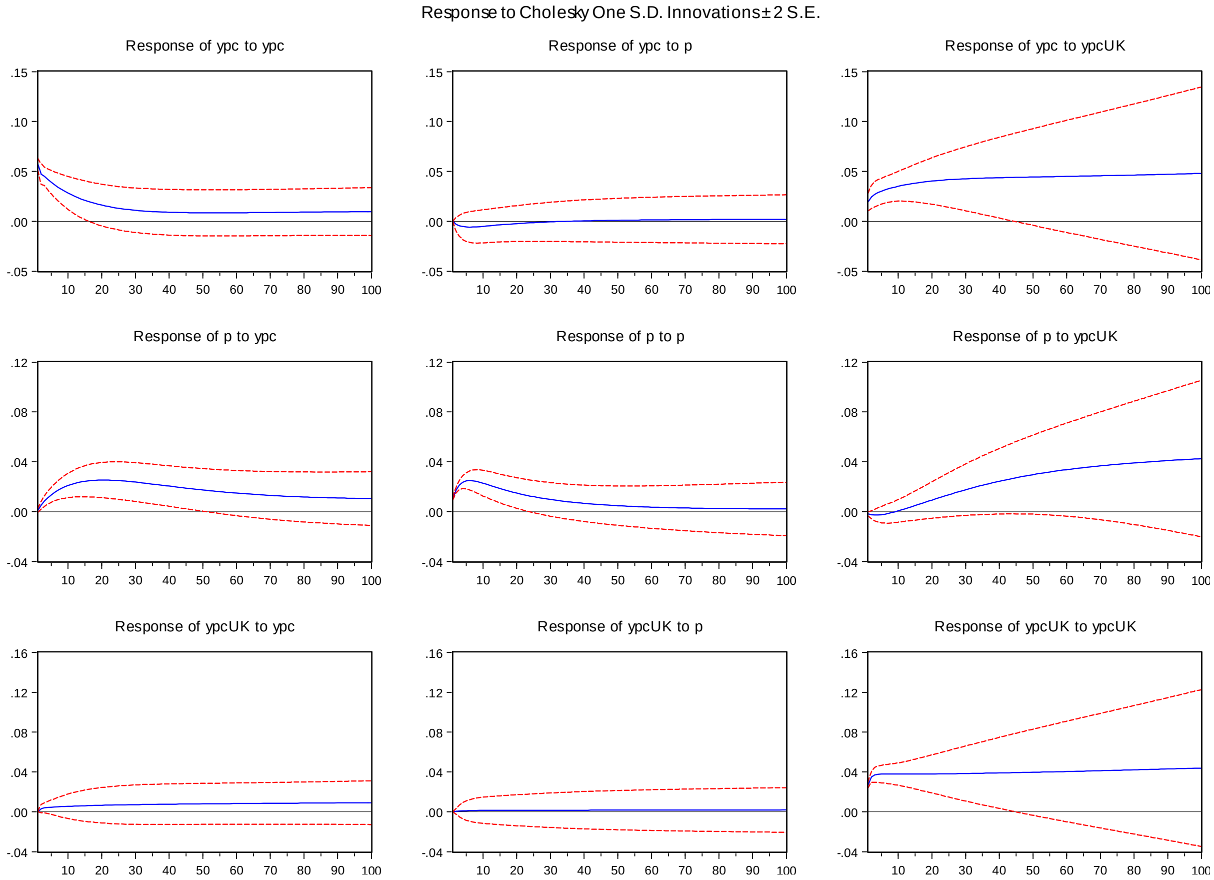


Figure 5: Recursive VAR(2) (ypc_{uk}, ypc, p) 1832 to 1945

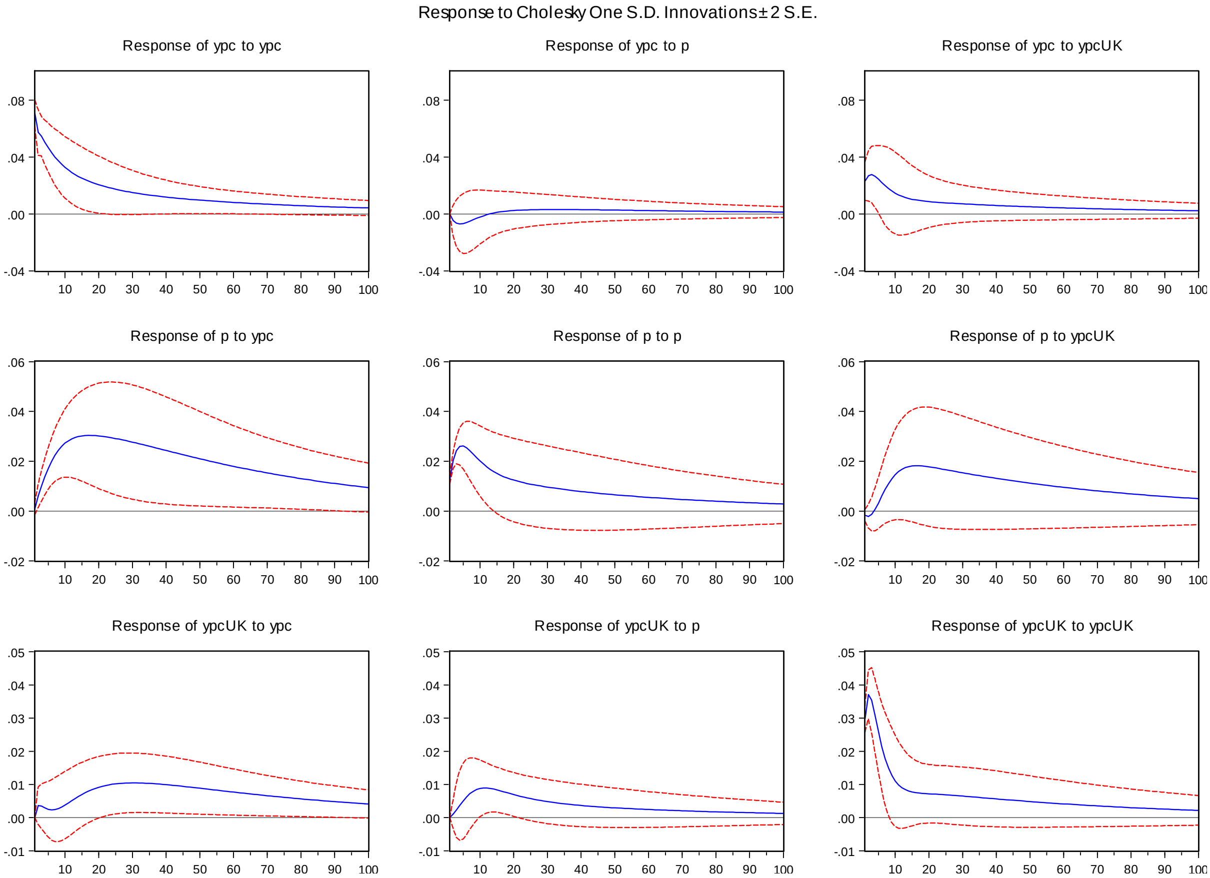
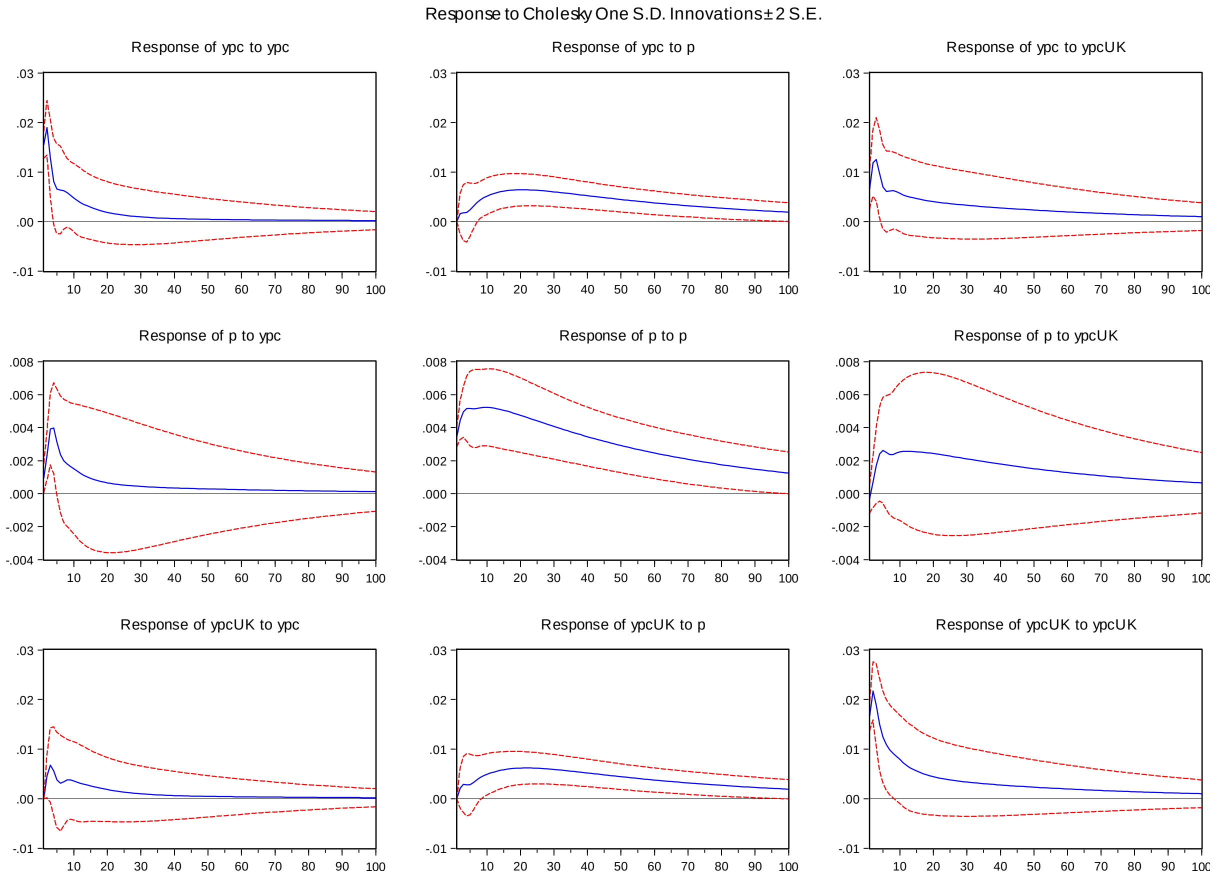


Figure 6: Recursive VAR(3) (*ypc*$_{uk}$*, ypc, p*) 1945 to 2008



Appendix 4: Johansen tests[(a) (b)] for cointegrating relationships between *ypc, p,* ypc_{uk}

ypc, p				
1823-2008				
Rank	Eigenvalue	Trace Statistic	Critical Value	p-value
r=0	0.089	18.831	12.321	0.00
r≤1	0.0079	1.471	4.130	0.26
Rank	Eigenvalue	Max-Eigen Statistic	Critical Value	p-value
r=0	0.089	17.361	11.225	0.00
r≤1	0.0079	1.471	4.130	0.26
1823-1945				
Rank	Eigenvalue	Trace Statistic	Critical Value	p-value
r=0	0.093	19.662	12.321	0.00
r≤1	0.060	7.593	4.130	0.01
Rank	Eigenvalue	Max-Eigen Statistic	Critical Value	p-value
r=0	0.093	12.069	11.225	0.04
r≤1	0.060	7.593	4.130	0.01
1945-2008				
Rank	Eigenvalue	Trace Statistic	Critical Value	p-value
r=0	0.325	27.994	12.321	0.00
r≤1	0.043	2.799	4.130	0.11
Rank	Eigenvalue	Max-Eigen Statistic	Critical Value	p-value
r=0	0.325	25.195	11.230	0.00
r≤1	0.043	2.799	4.130	0.11

ypc, p, ypc_{uk}				
1833-2008				
Rank	Eigenvalue	Trace Statistic	Critical Value	p-value
r=0	0.110	30.777	24.276	0.01
r≤1	0.056	10.262	12.321	0.11
r≤2	0.000	0.038	4.130	0.87
Rank	Eigenvalue	Max-Eigen Statistic	Critical Value	p-value
r=0	0.110	20.514	17.797	0.02
r≤1	0.056	10.225	11.225	0.08
r≤2	0.000	0.038	4.130	0.87
1834-1945				
Rank	Eigenvalue	Trace Statistic	Critical Value	p-value
r=0	0.167	34.213	24.276	0.00
r≤1	0.087	13.712	12.321	0.03
r≤2	0.031	3.556	4.130	0.07
Rank	Eigenvalue	Max-Eigen Statistic	Critical Value	p-value
r=0	0.167	20.501	17.797	0.02
r≤1	0.087	10.157	11.225	0.08
r≤2	0.031	3.556	4.130	0.07
1945-2008				
Rank	Eigenvalue	Trace Statistic	Critical Value	p-value
r=0	0.354	33.883	24.276	0.00
r≤1	0.085	5.950	12.321	0.44
r≤2	0.004	0.254	4.130	0.67
Rank	Eigenvalue	Max-Eigen Statistic	Critical Value	p-value
r=0	0.354	27.932	17.797	0.00
r≤1	0.085	5.696	11.225	0.39
r≤2	0.004	0.254	4.130	0.67

Notes: (a) Test statistics based on $\Delta y_t = \alpha(\beta y_{t-1}) + \sum_{i=1}^{k-1} \Gamma \Delta y_{t-i} + \varepsilon_t$. (b) MacKinnon-Haugh-Michelis *p*-values.