Labor Market Adjustments to Population Decline: A Historical Macroeconomic Perspective, 1875-2019

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Abstract

Advanced economies will face population decline, particularly among those of working age. Yet, evidence of labor market implications is sparse. Creating a historical dataset for sixteen advanced economies from 1875 to 2019, we identify population shocks and trace the economic effects conditionally on the demographic regime. Our results suggest regime-specific differences: First, population decline quickly passes through to the labor market, translating into swifter disinvestment and declines in employment, but the effects of population growth take time. Second, during population decline, labor force participation increases in response to reduced labor supply. Likewise, initially swift disinvestment tendencies decelerate. Consequently, we find only incomplete capital adjustment. Third, despite declining labor supply, we find neither decreases in unemployment nor significant changes in wages. Finally, while population decline tends to depress total factor productivity, our results indicate that negative effects for economic growth are mitigated by increases in participation and the capital-labor ratio. (JEL: J11, J21, E22, E24)

Keywords: Population decline, labor market adjustments, historical dataset, smooth transition regression, proxy VAR

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1 Introduction

A hitherto stylized fact, the perpetual growth of the population, is questioned in the short to medium and the long term by a range of demographic forecasts across countries (e.g., UN, 2019). In the years and decades to come, depending on the scenario under consideration, advanced economies will face a stagnation and, sooner or later, a secular decline of their populations. Thus, in stark contrast to the more recent population history, the impending transformations will be pronounced, widespread, and enduring, providing a changed demographic context for a wide range of advanced economies. The decline is expected to be even more pronounced among those of working age, which is particularly relevant from an economic perspective.[1]

Given the issue's contemporary and future relevance across countries as well as the importance of demography for economic growth in general and the labor market in particular, questions about the economic implications of population decline emerge. Ultimately, the expected developments may challenge other supposedly stylized facts as well, such as the ever-accelerating growth of GDP (per capita) (Jones and Romer, 2010) or the constant labor share in national income (Kaldor, 1961).

However, despite its occurrence or imminence in most advanced economies, there is substantial under-coverage among theoretical and empirical research on the economic implications of population decline, in general as well as with regard to the labor market. In formal economic modelling, most approaches assume a growing, or at least stagnant, population (Jones, 2022). On the contrary, population decline and the accompanying implications have hardly been discussed as yet. In the existing literature, there have been some attempts to investigate the effects of demographic changes in Ramsey-type models (Brida and Accinelli, 2007; Kajanovičová et al., 2020), Solow-type models (Sasaki, 2019), or endogenous and semi-endogenous growth models (Christiaans, 2011; Jones, 2022; Sasaki and Hoshida, 2017). Among empirical studies, the under-coverage is even more distinct and may be explained by the fact that there have been comparatively few periods of population decline among advanced economies in the recent past, hampering the reliable identification of its effects. Consequently, existing macroeconomic research on the demography-economy nexus focuses on a variety of different issues: a multitude of empirical studies analyze the effects of population growth (see Headey and Hodge 2009 for a comprehensive meta-study) on economic growth, while others investigate the consequences of population ageing (e.g., Acemoglu and Restrepo, 2017, 2022; Börsch-Supan, 2008) or changing mortality, fertility, and human capital patterns (for many: Barro, 1991, 1998; Barro and Lee, 1994; Bloom and Williamson, 1998; Hall and Jones, 1999; Galor and Mountford, 2008). From a more conceptual perspective, both the secular stagnation

[1] As we focus on working-age population (15 to 64 years) from here onwards, we use the terms working-age population and population interchangeably.

debate (Eggertsson et al., 2019) and the unified growth theory (Cervellati et al., 2017), among others, have addressed the role of demography for long-term economic development. But as in theory, population decline has not yet drawn explicit attention in the empirical literature.

Importantly, sparse contributions, such as the one more recently by (Jones, 2022), suggest that the economic effects of growth and decline in the population do not need to follow symmetrical paths. Yet, whether this applies to labor market issues as well – such as the behavior of wages, the capital utilization of firms, or the elasticity of labor supply when the labor force is declining – has hardly been addressed so far, neither in theory nor in empirics. To provide an empirically substantiated starting and orientation point for both policy and future research, such as the incorporation of labor market adjustments to population decline in formal modelling, we examine the effects of population decline on the labor market from a historical macroeconomic perspective.

Operationalizing our analysis consists of three key components. First, the occurrence of periods of actual population decline and the availability of labor market data do not necessarily coincide. As noted above, for most advanced economies, population shrinkage appears to be a rather new phenomenon. However, if we take a more historical perspective, even back to the second half of the 19th century, we are able to identify several periods of decline and low population growth, distributed across several countries. On the one hand, this suggests to empirically investigate population decline and its macroeconomic implications in a historical cross-country framework. On the other hand, economic data availability proves to be sparse in the very long run. To this end, we compiled a new historical dataset from a large number national and international sources. We collected information on population, births, real GDP, real wages, real investment, employment, unemployment, labor force participation, and hours worked for sixteen countries from more than 100 different sources, providing an annual coverage for seven countries from 1875 to 2019 and for nine from 1900. Second, the estimation must adequately address possible nonlinear interdependencies of macroeconomic variables conditional on the prevailing demographic regime. To account for this, we specify a panel smooth transition VAR (PSTVAR), thereby contributing to growing bodies of literature that rely on, first, cross-country settings (e.g., Aksoy et al., 2019), and second, regime-dependent methods (e.g., Auerbach and Gorodnichenko, 2012) in analyzing dynamic interdependencies of macroeconomic aggregates. Third, tracing possibly nonlinear responses to population decline requires an appropriate identification of the structural population shock. By relying on external instruments, or proxy variables, we follow another strand of recent research (e.g., Gertler and Karadi, 2015; Mertens and Ravn, 2013; Stock and Watson, 2018). Drawing on lagged births data as an instrument for working-age population inflows and outflows, we identify the contemporaneous effects of a structural population shock in times of population growth and decline and trace the corresponding impact of the structural shock using orthogonal impulse response functions.

Our findings indicate differences in the effects of population changes and corresponding adjustments across regimes. In general, population changes pass through to the labor market more quickly in times of decline, translating, inter alia, into a swifter decline in employment and disinvestment compared to times of growth. In the medium to long term, regime-specific adjustment processes unfold. In periods of population decline, labor force participation increases as a response to the initially quick reduction of labor supply, likewise disinvestment tendencies decelerate. By contrast, the effects of population growth unfold lagged but steadily. Notably, we do not find decreases in unemployment or any significant changes of wages as a shortage indicator in times of population decline. Thus, while population decline tends to depress total factor productivity, as also discussed by the literature, our findings indicate that corresponding negative effects for economic growth are mitigated by increases in participation and capital intensity.

The remainder of the paper is structured as follows. In section 2, we provide an illustrative overview of the role of population and labor force size in theoretical models to motivate the empirical investigation in this paper. Subsequently, and complementary to the survey on theoretical considerations, we provide some descriptive statistics on population decline in the past, introduce our historical dataset, and offer stylized evidence on trajectories of labor market variables during periods of decline in section 3. Based upon these two parts, section 4 outlines a suitable nonlinear econometric strategy to identify (possibly) asymmetric effects of population changes during times of growth and decline. The corresponding results are presented and discussed in section 5. The last section concludes.

2 Theoretical Perspectives: Reference Points

In general, considerations on the economic effects of population decline depart from the fact that even in the simplest production function, $Y = f(K, L)$, the supplied amount of labor, L, is a crucial input determining economic growth. Yet, the literature analyzing the economic effects of population decline remains limited. A view across different approaches that investigate the population-economy nexus offers some reference points to guide our empirical investigation of the economic effects of population decline.

2.1 Population decline and economic growth

In a typical, generic macroeconomic growth model (see standard textbooks, such as chapters 1 and 2 in Romer 2019), the population consists of a given number n of households with an identical number of household members, H_t, growing at a constant rate $g > 0$ over time:

$$H_t = H_0 e^{gt} \tag{1}$$

Here, each member of each household inelastically supplies one unit of labor, thus at each point t in time

$$P_t = nH_t = L_t \tag{2}$$

i.e., the population size equals the size of the labor force. Thus $g = s$, meaning the growth rate of the population is identical to the growth rate of the labor supply, s. In the simplest case, firms, using the given labor as well as capital input, are subject to common factor prices, given a level of technology, A_t, and produce according to the identical production function. Consequently, total output results as $Y_t = f(K_t, A_t L_t)$.

In this setting, capital and labor are complements – thus, ceteris paribus, a decrease in L_t causes a proportional decrease in output. Yet, those effects may already differ when assuming a production function of the form $Y_t = f(K_t^\sigma, A_t L_t^{1-\sigma})$ (Arrow et al., 1961), where σ is the elasticity of substitution between capital and labor. Here, depending on the value of σ, a decrease in L_t may be mitigated by exchanging for K_t and, thus, maintaining the output level even in the event of population decline.

The majority of macroeconomic research is still in rather early stages when it comes to analyzing the effects of population decline – only selected approaches deviate from the standard assumption of a constantly growing L_t and analyze the corresponding effects. Some have investigated the effects of population changes in a Malthusian framework. For instance, Voigtländer and Voth (2013) develop a model to show that the population decline in Europe caused by the Black Death explains a substantial part of increases in income per capita. Similarly, Young (2005) analyzes the effect of the AIDS epidemic on per capita consumption in South Africa, finding an enhancing effect.

Yet, the imminent population decline across advanced economies is different from epidemic-induced declines, often suggesting transition periods from high growth to low growth, stagnation, and eventually decline (UN, 2019). In this context, authors have investigated the effects of changes in the population growth rate in Ramsey-type growth models, for example when population growth is logistic (Brida and Accinelli, 2007). Sasaki (2019) analyzes the consequences of negative population growth on the long run growth rate of per capita output using a Solow-type growth model. He demonstrates that, if in such a setting the elasticity of substitution is less than unity, economic growth exclusively depends on the rate of technological progress. Christiaans (2011) as well as Sasaki and Hoshida (2017) use semi-endogenous growth models to investigate the effects of population decline on output per capita. The results suggest varying responses of economic growth to negative population growth, inter alia depending on the assumed depreciation rate of capital. Sasaki (2023) uses a Solow growth model with automation capital and shows that the population decline and economic growth can coincide. Notably, the results indicate that the absolute value of population decline may play an important role.

In a more recent contribution, Jones (2022) demonstrates that, in the case of population decline, endogenous and semi-endogenous growth models lead to stagnating living standards and knowledge. The underlying mechanism resembles the established endogenous growth literature (among many: Romer, 1986, 1990), in which ideas determine economic growth, and depend themselves on the population size (for a discussion, see Dinopoulos and Thompson, 1999). But by taking one step further and endogenizing fertility, Jones (2022) shows that economic growth can only be resumed if the economy switches to an optimal allocation soon enough. Other recent contributions challenge the stagnation scenario. Strulik (2023) augments the model of Jones (2022) by endogenous education components and human capital as an input factor of production. Similarly, Boikos et al. (2023) build an R&D-based growth model with human capital accumulation and Bucci (2023) uses an endogenous growth model with human capital accumulation. In these theoretical settings, economic growth and population decline may coexist. Also, Elgin and Tumen (2012) elaborate on findings along this line.

Thus, the questions whether population decline and economic growth can coexist, and whether population decline negatively affects TFP, have not been fully resolved yet. Hypotheses on these issues serve as a first reference point for our empirical investigation. Similarly, the role of capital, as the other factor input, and the question to which extent capital adjustment may unfold in response to population decline, serve as another.

2.2 Population decline and margins of labor supply and demand

Even though L is arguably closely connected to the size of the population, P, both are not identical. Descriptive empirical evidence shows that neither participation rates are 100 percent nor working hours are evenly distributed across individuals and time (OECD, 2022).

However, in economic research, questions concerning causes and effects of changes in the size and composition of L are often addressed separately, by different parts of the literature and model families, and are not necessarily linked to population decline. The insights delivered by the contributions surveyed above are substantial, but hardly deviate from the assumption of $P_t = L_t$. Yet, if labor supply side dynamics are more complex than the inelasticity assumption in equation (2) suggests, actual labor supply should rather be understood as

$$a_t h_t P_t = L_t \tag{3}$$

where a_t is the labor force participation rate (extensive margin) and h_t is the average hours worked (intensive margin) at time t. Important adjustment mechanisms to demographic changes may unfold through these channels. Existing (micro- and macroeconomic) empirical and theoretical approaches have addressed them in different settings and have also investigated interactions of changing labor supply with the labor demand (firm) side.

It is conceivable that demographic shrinkage my be offset by rising labor supply that comes as a reaction to higher wages. That hinges on labor supply elasticities. The idea is based on an individual's (a household's) utility function, $U = f(c, l)$, encompassing consumption, c – which, in the absence of non-labor income, is solely determined by the wage rate and the supplied hours of work – and leisure, l. Approaches have analyzed elasticities of hours and participation in different settings, often suggesting positive effects of wage increases. This applies in particular, but not exclusively, on the extensive margin (among many: Ashenfelter et al. 2010; Bargain et al. 2014; Blundell et al. 2013; Chetty 2012; Evers et al. 2008; Keane and Rogerson 2012; for a discussion on the variation in estimates of labor supply elasticities, see Bargain and Peichl 2016).

Logically, a relevant question is in how far population decline triggers wage growth. In view of labor supply decline, one may postulate an increase of wages as a shortage indicator. This assumption can be traced back, for example, to the literature on the wage curve, discussing a linear connection between higher unemployment and lower wages (Blanchflower and Oswald, 1995), with the former usually perceived as a sign of underutilized labor supply. Results from Voigtländer and Voth (2013) and Young (2005) for epidemic population declines also support the role of the shortage channel.

But of course, population decline may affect the economy beyond labor supply, thus triggering further adjument processes. These can involve the capital and labor demand side, too. The standard law of labor demand suggests that rising wages reduce a firm's labor demand, depending on mediating factors such as substitutability (Hamermesh 1993; for a detailed survey on labor demand elasticities, see Lichter et al. 2015, for example). In a recent contribution, Bossler and Popp (2023) augment the law of labor demand by hiring costs. They demonstrate that not only rising wages but also general labor market tightness reduces the labor demand of firms, rather than increasing it, as searching becomes costlier. These findings suggest that even if a slack labor market reduces wages, a tight labor market does not necessarily cause rising wages. Thus, ex ante, the effects of population decline on labor supply and wages are unclear. The above considerations serve as a third reference point for the empirical analysis.

The brief illustrative overview demonstrates that from the existing body of theoretical literature, the economic effects of changes in the population size are difficult to derive and may depend on the interaction of a series of relevant factors, such as wages or hours worked[2], and this interaction may itself be state-dependent. This calls for empirical evidence on the causal effects of population shrinkage in order to learn about the potential future path of many economies and to inform further theory development.

[2]Of course, numerous contributions have documented factors impacting both the supply and demand of labor beyond wages as the single determinant – such as the institutional setting and policies, for example in fostering or hampering female labor force participation (among many: Costa 2000; Cipollone et al. 2014; for an exemplary survey see Abraham and Kearney 2020).

3 Population Decline and the Labor Market: Some Descriptive Statistics from a New Historical Dataset

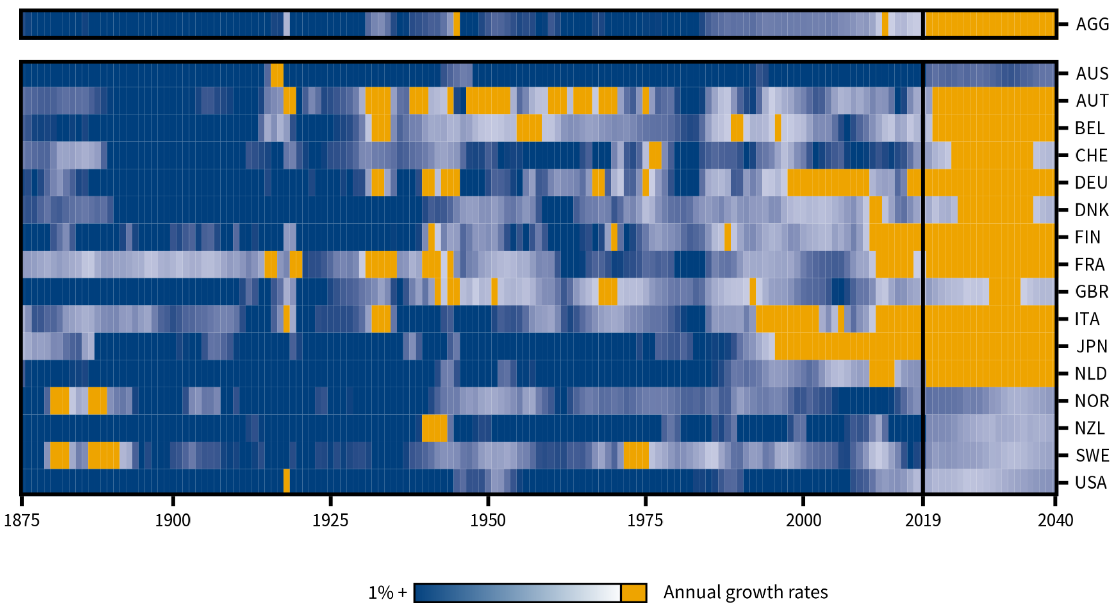
3.1 Population decline: occurrence and characteristics

The under-coverage of population decline in (economic) research, as outlined above, is accompanied by similarly sparse descriptive statistics on the nature of population decline in the past; that is, the frequency of its occurrence, magnitude, distribution, and duration. A view on the historical data for annual working-age population change among selected advanced economies from 1875 to 2019 in Figures 1, 2 and Table 1 provides insights.

First, the vast majority of years during the past one and a half centuries have been years of population growth (blue in Figure 1): 154 of 2096 observations, or 7.3 percent, were decline years (orange), as Table 1 reveals. Additionally, there have been several periods of low population growth (light blue). Over the whole period covered, the median annual change of the working-age population was 0.85 percent, with 0.91 in growth years and –0.26 in decline years, and with the strongest increases in overseas migration destinations in the 19th century as well as the strongest decrease during Japan's ongoing decline since the 1990s. For all observations, the interquartile range goes from 0.38 to 1.30 percent, illustrated in Figure 2. Among growth observations, our data has an interquartile range from 0.48 to 1.33 percent, and among decline observations from –0.45 to –0.10 percent.

Second, as Figure 1 illustrates, population decline tends to occur consecutively, forming

Figure 1: Aggregate and individual working-age population growth across advanced economies, 1875–2040



Author's own calculations. First line (AGG) indicates the dynamics of the total population among the sixteen countries below. For information on data sources, see the Online Supplement.

Table 1: Descriptive statistics on annual working-age population changes, 1875 − 2019

	Descriptive statistics on annual working-age population change (in percent)									
	Total						Growth years		Decline years	
	n	Median	Mean	Min	Max	SD	n	Median	n	Median
1875−2019	2096	0.85	0.90	–1.40	10.63	0.77	1942	0.92	154	–0.26
1875−1969	1296	1.05	1.10	–1.10	10.63	0.80	1238	1.08	58	–0.21
1970−2019	800	0.54	0.59	–1.40	3.40	0.60	704	0.62	96	–0.30

Figures in this table encompass working-age population data from the sixteen countries covered by the historical dataset over the period 1874–2019 but exclude observations in war years (1914–1919 and 1939–1946). Author's own calculations. For information on data sources, see the Online Supplement.

phases of shrinkage rather than single years. In the historical data, we are able to identify 34 periods of consecutive decline[3], whereby the median length was three years. The median *peak-to-through* (compare Reinhart and Rogoff 2014 on GDP changes in the course of financial crises) magnitude, i.e., the median cumulative decline in a shrinkage period, was –0.48 percent.

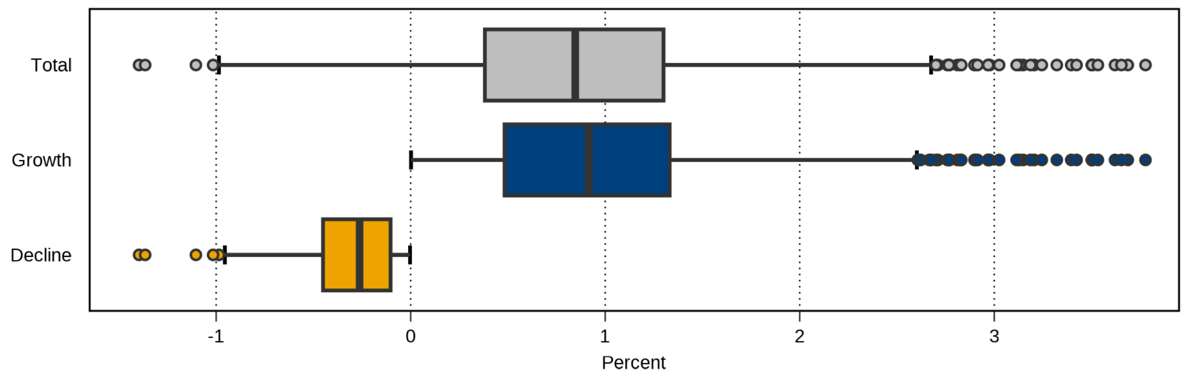
Third, occurrence differs across countries. Some have never faced working-age population decline in non-war years (Australia, New Zealand, United States), whereas others have repeatedly undergone shrinkage periods, although with differing duration and magnitude. Japan has experienced the most non-war years (25) of working-age population shrinkage, followed by Austria and Italy (22) as well as Germany (21) with some shorter sequences distributed across the whole observation period. Also, the underlying drivers of population decline differ, ranging from overseas emigration in the late 19th century, inter alia due to economic reasons such as wage differentials (Hatton and Williamson, 1998), to below-replacement fertility over decades in more recent time. Later, we use an instrument based on lagged births in order to avoid endogeneity stemming from any such current shocks.

Notably, there has been more pronounced growth in the years before 1970 compared to those afterwards, vividly demonstrating the secular decline of population growth in the very long run. By contrast, population decline observations have been much more similar over time, whereby 43 of the 96 decline observations after 1970 have occurred since 2010. And notably, the median of the decline observations in the past (−0.26 percent) is remarkably close to the median of projected decline observations in the same countries between 2019 and 2040 according to UN (2019) (−0.23 percent).

Over the decades and across advanced economies, persons aged 15 to 64 years account for almost the entire workforce (see, e.g., ILO, 1977a,b; OECD, 2022), and these age brackets are widely used to define working age. Importantly, one may argue, against the backdrop of the ongoing population ageing across advanced economies, that this definition should

[3] Notably, for this illustrative purpose, we define a period to be one or more years of consecutive decline. A period starts whenever there is a decline of the population and there has not been a decline in the preceding two years, avoiding to count one period of decline as two due to very low growth in between. We exclude those periods that started during war years as defined above.

Figure 2: Distribution of annual population change observations in times of growth and decline



Observations included correspond to Table 1. Whiskers indicate 1.5 IQR. Five outliers among the growth observations that are larger than 4 percent are not displayed for illustrative purposes. Author's own calculations. For information on data sources, see the Online Supplement.

also encompass persons aged 65 to 69 years, given rising participation rates. But in the historical setting of out paper, including those aged 65 to 69 years is not feasible due to limited availability beyond the more recent past, as coverage for one half of our sample starts only in the 1990s or 2000s. Second, despite recent increases, participation rates in this age group are also still low - the median of the 2010s was at 19.2 percent (OECD, 2024). Jointly, these points render a definition of working age as those aged 15 to 64 years not only necessary but also justified.

3.2 Historical labor market dataset: a short overview

A substantial share of the empirical literature using macroeconomic aggregates in (dynamic) panel models draws on time series starting in the 1960s, 1970s, or later, in particular in a cross-country perspective, with varying frequencies (e.g., Aksoy et al. 2019; Antonakakis et al. 2017; Canova et al. 2007; Comunale 2022; among others). Additionally, also labor market statistics across countries, most importantly information on unemployment, such as those delivered by the OECD, start around the mid-1960s or later, indicating this period as a somewhat natural starting point for empirical analyses. Yet, as noted above, striving to cover a sufficient set of periods of population decline, we exploit observations as early as 1875.

Such an exploration of historical economic dynamics across countries is a notoriously difficult task, particularly when focused on labor market issues. Well-known data collections such as the International Historical Statistics (Mitchell, 2013) or Maddisons Historical Statistics (Bolt and van Zanden, 2020) and their respective predecessors, among others, have settled the path for comparative historical economic research for decades. However, the availability of annual data in the very long run remained limited to selected variables. We have seen substantial improvements in recent years by compilations such as the Macrohistory Database (Jordà et al., 2017) or the Long-Term Productivity Database (Bergeaud et al., 2016), both starting in the second half of the 19th century, covering a variety of advanced economies, and broadening the range of macroeconomic indicators. But the availability of annual information on variables such as unemployment is still strongly limited.

Based upon this finding, and in order to operationalize an analysis of macroeconomic labor market adjustments to population decline, we compiled a new historical annual labor market dataset, stemming from extensive data acquisition efforts. On the one hand, we draw both on existing macroeconomic and demographic databases, such as those quoted above, the Human Mortality Database (HMD, 2023) or various OECD statistics. On the other hand, and more importantly, we rely on a vast number of individual (national) data sources and collections. Overall, the compilation combines information from more than 100 different sources. The historical dataset covers sixteen advanced economies, seven of which starting from 1875 (Denmark, Germany, Netherlands, Norway, Sweden, United Kingdom, United States) and nine (Australia, Austria, Belgium, Finland, France, Italy, Japan, New Zealand, Switzerland) starting from 1900 due to limited data availability. The collection contains annual information on demographic and economic variables until 2019, which are population by age groups, real GDP, real wages, real investment, total employment, the unemployment rate, and average annual hours worked. Figure 3 provides a broad and descriptive overview of the dataset.

3.3 The labor market in times of decline: descriptive evidence

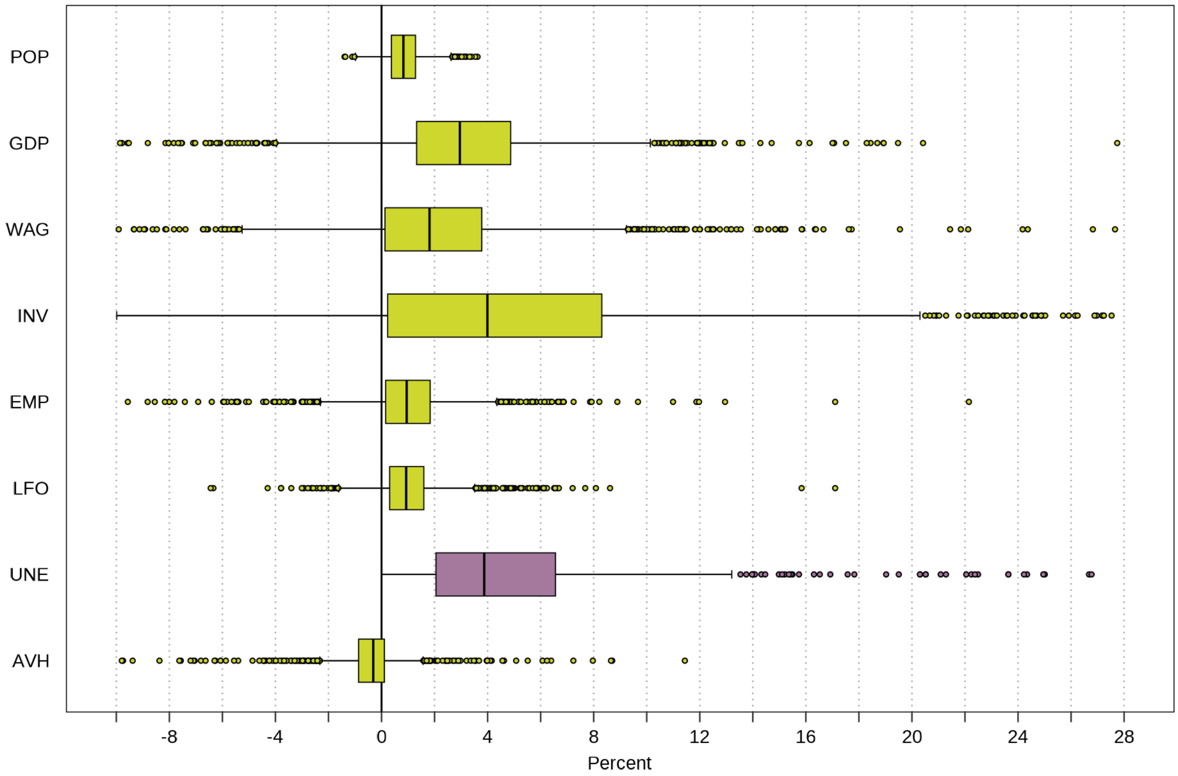
Given that decline usually persists over several years, one may also assume that adjustment processes unfold over a longer time span. In Figure 4, the dynamics of working-age population as well as of the labor market variables in advance of and during periods of population decline are displayed as solid orange lines, with the levels[4] being indexed to the last year before the decline started ($t0$). The displayed dynamics are those of annual median values, covering six years prior to the decline period and five years of the decline period itself (gray background).[5]

Most notably, population growth rates had already been low prior to the respective decline. This implies the intuitively appealing fact that population decline is generally preceded by phases of low growth, respectively stagnation. In other words, switches be-

[4]Since we include the labor force rather than unemployment in the estimation outlined below, we display the labor force here as well.

[5]Notably, we display the median values of all periods; that is, both those that have ended earlier than five years and those that have ended later than the displayed horizon.

Figure 3: Distribution of the variables in the historical dataset

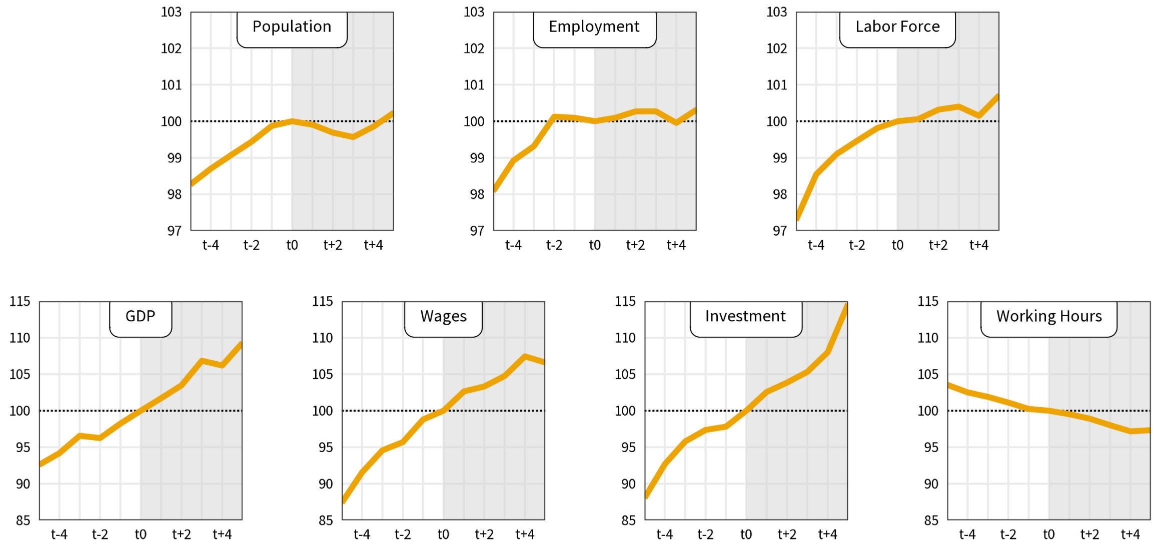


Observations included correspond to Table 1. Whiskers indicate 1.5 IQR. Outliers above 20 percent and below −10 percent have been excluded for presentation. Abbreviations: POP = working-age population, GDP = real GDP, WAG = real wages, INV = real investment, EMP = employment, LFO = labor force, UNE = unemployment rate, AVH = average annual hours worked. Green colored boxplots indicate data for annual changes in percent, the purple colored boxplot indicates the unemployment rate in percent of the labor force. Author's own calculations. For information on data sources, see the Online Supplement.

tween a regime of strong, or at least average, population growth and a shrinkage regime take place generally more slowly than quickly. Moreover, the dynamics of labor market variables exhibit differences. For example, wages and hours worked closely stick to the pre-decline trend, indicating limited effects of population decline. On the other hand, there is low employment and labor force growth prior to the decline mirroring low population growth rates, followed by very similar patterns once decline occurs, suggesting a more pronounced effect for these variables.

Obviously, these findings are stylized, neither causal relations nor dynamic interdependencies of the examined macroeconomic aggregates are appropriately mirrored. Put differently, descriptive evidence as shown in Figure 4 does not allow the inference of the causal effects of population decline on labor market variables of interest, and it also does not consider how distinct and enduring a particular decline period has been.

Figure 4: Stylized evidence of labor market dynamics before and during population decline periods



The figure displays dynamics before, during and after periods of population decline as explained in the main text. Author's own calculations. For information on data sources, see the Online Supplement.

3.4 Towards an empirical framework

The short analysis in this section implies there are four directions that an empirical analysis aiming to carve out possibly nonlinear macroeconomic effects of population decline needs to follow. First, a suitable empirical strategy must identify the causal effect of positive, respectively, negative population changes, distinguishing it from other shocks in the economy, and clearly examine the dynamic adjustment process over time that may differ in times of growth and decline. Second, simply distinguishing population growth and decline into two separate regimes does not account for empirically observed demographic developments. Rather, choosing an estimation setting that allows the impact of population changes to differ continuously from high to low growth to decline takes the existence of population stagnation before and after periods of decline into account. Third, the sparse occurrence of population decline calls for a cross-country perspective. Identifying nonlinear effects of population changes in growth and decline periods using an econometric model requires a sufficient number of observations for both, which is clearly not given when focusing on an individual economy. Even for countries that experienced comparatively many years of decline, a dynamic analysis including more than two or three variables with a sufficient number of lags quickly depletes its degrees of freedom for decline periods. Fourth, even in a cross-country perspective, there have been only few observations in the more recent past, calling to exploit the full variation of population changes not only across countries but also over time, whenever reliable labor market data exist. Below, we propose an estimation framework addressing the mentioned necessities.

4 Econometric Strategy

As outlined, we exploit the time-series variation from multiple countries to identify possibly differing effects of population growth and decline, using an empirical strategy that permits the analysis of dynamic interdependencies conditional on the demographic regime. We draw on and expand different strands of the literature and introduce a suitable external instrument to identify the effects of a structural population shock in the economy. We divide this section into a series of subsections on nonlinear dynamic modelling, regime specification, shock identification, instruments, and impulse responses.

4.1 Capturing nonlinear effects: Panel Smooth Transition VAR

We start by specifying a panel VAR, and in doing so, we contribute to a growing body of literature making use of panel VARs in macroeconomics (e.g., Aksoy et al., 2019). Applying a vector autoregressive structure allows the flexible analysis of macroeconomic interdependencies without a priori imposing assumptions on the directions of effects (Canova and Ciccarelli, 2013). Drawing on this literature, we specify our model in its linear version as

$$Y_{it} = \mu_i + \delta_t + AY_{i,t-1} + EX_{it} + u_{it} \tag{4}$$

with $i = 1, \ldots, c$ and $t = 1, \ldots, T$; c and T being the panel and time dimensions, respectively. Y_{it} is the vector of endogenous variables, μ_i and δ_t denote country- and time-fixed effects, respectively, and X_{it} represents country-year dummy variables to capture the effects of war and interwar periods.[6] A and E are coefficient matrices. Y_{it} comprises seven variables: the working-age population, real GDP, real wages, real investment, employment, the labor force, and average annual hours worked. All variables are included as log levels. Notably, given the inclusion of Y_{it} in levels, when allowing for a sufficient lag length, the VAR is able to capture level relations and flexibly form quasi-differences in the presence of unit roots (see, e.g., Sims et al. 1990; more recently Weber and Weigand 2018).

Since the focus of the present paper is on the analysis of potentially different effects of population decline compared to population growth and the descriptive evidence suggests a continuous rather than a threshold modelling approach, we combine our panel VAR with a nonlinear smooth transition structure. This follows a strand of literature using common vector autoregressive models and nonlinear extensions to account for regime-wise

[6] This vector of dummy variables eliminates the effects of all observations from 1914 to 1922 as well as from 1929 to 1949, and is basically equal to removing those observations from the panel dataset completely. We keep these observations and eliminate the corresponding effects using dummy variables instead of excluding them in order to easily carry out the residual resampling. We additionally include a dummy for the German hyperinflation in 1923.

interdependencies of macroeconomic variables (e.g., Auerbach and Gorodnichenko, 2012). Thus, our linear model in (4) is modified as follows

$$Y_{it} = \mu_i + \delta_t + [1 - P(q_{it})]GY_{i,t-1} + [P(q_{it})]DY_{i,t-1} + EX_{it} + u_{it} \quad (5)$$

where G and D are matrices holding the regime-dependent coefficients of the endogenous variables, and $P(q_{it})$ refers to the probability of experiencing population decline. This probability is given as

$$P(q_{it}) = \frac{exp[-\gamma(q_{it} - \kappa)]}{1 + exp[-\gamma(q_{it} - \kappa)]} \quad (6)$$

where q_{it} is the transition variable, γ defines the smoothness of the transition, and κ is a location parameter defining the value of q_{it} at which the regime-switch occurs.

By using the framework in (5), we exploit the effects of varying population growth and decline rates within countries over time, while the differences between countries, such as their sizes or other fixed-effects, are accounted for by the inclusion of μ_i.

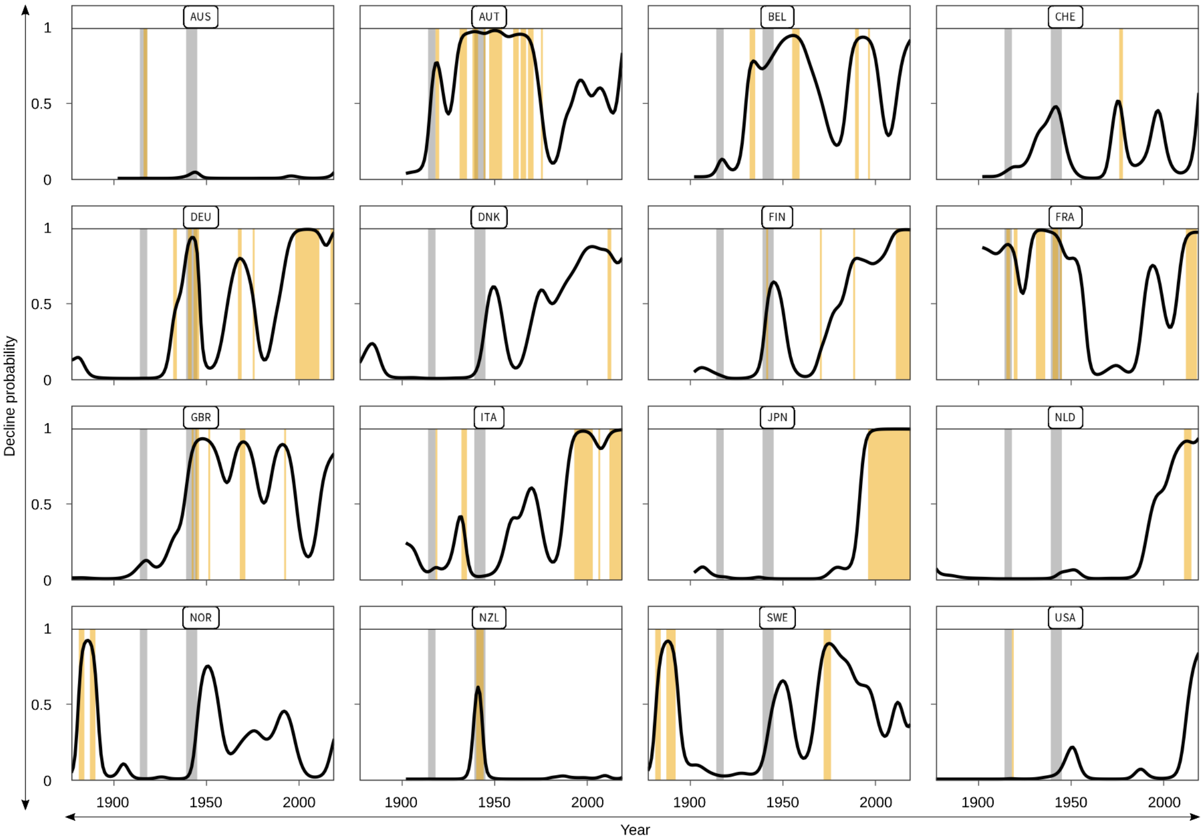
4.2 Demographic regimes: transition variable and smoothing parameters

Given the scope of the paper, the transition variable q_{it} incorporates information on the prevailing demographic regime, i.e., population growth rates. However, from a conceptual perspective, the selection of an appropriate transition variable is not straightforward. Moreover, the smoothing and location parameters γ and κ are not predefined either. In the literature (e.g., Auerbach and Gorodnichenko, 2012; Gehrke and Hochmuth, 2021), authors tend to select a transition variable, define a switching point κ, and then calibrate γ such that the share of observations with probability $\geq 1 - \tau$ is close or equal to τ, which is the share of observation in the regime of interest, e.g., years of population decline.

The selection of a transition variable mainly translates into the question of which period of population change is relevant to depict a demographic regime under which a labor market operates. To answer this question, we use the trend of annual population growth rates as delivered by the HP filter ($\lambda = 100$) as our transition variable. To avoid the common bias of the HP filter at the ends of the sample, we use population growth rates from 1860 to 2025, using data sources as outlined in the Online Supplement.

For the switching point, the literature tends to define $\kappa = 0$, which, in case of the usual z-standardization of the transition variable, implies a switch at the mean. In our case, the plausibility of this switching point (0.63 percent) is disputable, as it implies that the majority of the years after 1970 is closer to the decline than the growth regime (compare Table 1), i.e., working-age population decline has been more likely than growth. This contrasts the narrative that extensive working-age population decline is a rather recent phenomenon. To find a more suitable switching point, we rely on the distribution of the

Figure 5: Decline probabilities across the countries in the sample



Shaded areas indicate war (gray) and decline (orange) years. Author's own calculations.

(original) annual population change rates in our dataset. We define $\kappa = Q_1^{POP,G,z}$, which is the lower quartile of growth observations across all years in the panel (0.48 percent) after the z-standardization of q_{it}. In the robustness section, we address this choice. Eventually, for calibrating γ, we follow the standard procedure in the literature as outlined above. The share of population decline observation in the observations across all countries in the final panel is 8.7 percent. In accordance with the literature, and to ensure a sufficient number of observations in each regime, we calibrate to the original share of decline observations. We set γ such that $Pr[P(q_{it}) \geq 0.913] \approx 0.087$. This calibration exercise yields $\gamma = 3.81$. Figure 5 illustrates the distribution of the decline probabilities stemming from this specification across the countries in our panel. As intended, the calibration exercise creates decline probabilities coinciding with actual decline observations and allows for smooth changes from and to periods of growth. Notably, by using the HP filter to smooth annual change rates, we capture only sufficiently long periods as decline (growth) periods. Single decline (growth) years in-between enduring periods of growth (decline) do not trigger regime changes. As a consequence, the median duration of periods where $Pr[P(q_{it}) \geq 0.916]$ is eight years. Having distributed growth and decline weights across all observations in the sample, we are able to estimate the model equations-wise by OLS. We check for the appropriate lag length by relying on the BIC, and arrive at a lag length of $p = 2$.

4.3 Identification of structural shocks by external instruments

However, to trace possibly nonsymmetrical labor market adjustments to population changes over time, we do not only estimate the reduced form, but we need to identify corresponding structural population shocks. Evidently, working-age population can be endogenous to economic variables, for example as push and pull factors driving migration. Indeed, estimations ignoring simultaneity in the Online Appendix demonstrate the importance of introducing instruments in the identification strategy.

In recent years, shock identification using external instruments has found widespread application (Gertler and Karadi, 2015; Stock and Watson, 2018). This approach exploits the well-known fact that the reduced form innovations, u_{it}, are a linear combination of structural shocks, ϵ_{it}:

$$u_{it} = S\epsilon_{it} \tag{7}$$

Analyses drawing on identification by external instruments refrain from identifying the full matrix S by imposing restrictions but rather focus only on the shock of interest, that is, only identify the corresponding column, s. To identify the structural shock of interest, $\epsilon_{1,it}$, appropriately, a suitable instrument, z_{it}, must satisfy the well-known conditions

$$E(\epsilon_{1,it} z_{it}) \neq 0 \tag{8}$$

$$E(\epsilon_{2:j,it} z_{it}) = 0 \tag{9}$$

While equation (8) states that z_{it}, must be relevant, i.e., correlated with the shock of interest, equation (9) requires the instrument to be exogenous to the remaining, unidentified shocks (Gertler and Karadi, 2015).

The contemporaneous effects of a structural shock are estimated by two-stage least squares (2SLS). In the first-stage regression, we isolate the structural shock; that is, we regress the residuals of the equation of interest, here of the population equation, $\hat{u}_{1,it}$, on the instrument. In the second stage, we identify the contemporaneous impact of the structural shock by regressing the residuals of our j equations, with $j = 1, \ldots, 7$, of the reduced-form estimation on the fitted values of the first stage. Notably, in the second stage, we weight the RHS by the respective regime probabilities. More formally, the regime-dependent, contemporaneous impact is given by

$$\hat{u}_{1,it} = \alpha + \omega z_{it} + v_{it} \tag{10}$$

$$\hat{u}_{j,it} = \beta + \theta_j^G [1 - P(q_{it})] s_{it} + \theta_j^D [P(q_{it})] s_{it} + r_{it} \tag{11}$$

where s_{it} is the structural shock in country i at time t, i.e., the fitted value obtained by estimating equation (10), ω is the coefficient in the first stage, and θ_j^G and θ_j^D hold the regime-dependent coefficients of interest. Importantly, by construction, this identification strategy scales the contemporaneous effects to a structural shock of 1 percent.[7] Yet, before estimating these regime-dependent, contemporaneous effects of a structural population shock as outlined, we need to find a valid instrument, meeting both the relevancy and exogeneity conditions.

4.4 Introducing a suitable instrument: lagged births

The development of a population can be written as $f(B, D, M)$, i.e., as a function of the three demographic components: births, deaths, and migration (Shryock and Siegel, 1976). Given our dataset starts in 1875, migration data is difficult, and for some countries impossible, to obtain, but information on natural population change – births and deaths – can be easily retrieved. However, as we strive to estimate the impact of a structural shock in the working-age population (15 to 64 years), the role of births differs from the role in the total population: The development of a working-age population can rather be written as $f(I, O, D, M)$, i.e., inflows into and outflows from the age group instead of births determine the size. Since we define the working-age population to be those aged 15 to 64 years, inflows in period t are persons aged 14 years in period $t-1$ and outflows in period t are persons aged 64 years in period $t-1$.

Notably, documenting annual births has a long tradition and corresponding time series are available starting from the early 19th century, and, by definition, a birth cohort always corresponds to a single age-year cohort in a given population. This observation suggests that inflows and outflows should be approximated by using lagged births data since, arguably, births lagged 15 and 65 years are an instrument that satisfies both conditions stated in equations (8) and (9). Nevertheless, the suitability of using births to identify a structural shock must take into account the interaction with the other two components of demographic changes, mortality and migration. Consequently, we conduct a series of preparatory steps.

First, mortality patterns have changed substantially over the past two centuries (Davenport, 2021). Correspondingly, the probability of a person reaching 15 and 65 years of age has been vastly different in the 19th century compared to the 20th and 21st century. An intuitive way of correcting for these changes and simultaneously relying on a variable of widespread availability is to weight births in a given year with some information on the life expectancy of newborns in the same year. However, life expectancy is typically calculated by using period mortality, i.e., the age-specific death rates in the same year or reference

[7] This applies to the linear case. When identifying the contemporaneous effect in a nonlinear framework, as in equation (11), this coefficient may be different from 1. In our case, these differences are small. Thus, we manually scale the contemporaneous effects accordingly.

period (see, e.g., Anderton et al., 1997; Shryock and Siegel, 1976). But this does not account for the impact that drastic events have on age-specific death rates, e.g., such as the effect of wars on the mortality of those who have already entered working age, as well as for general improvements in health care and longevity over centuries. Consequently, we weight births lagged 15 and 65 years, denoted as $B_{i,t-15}$ and $B_{i,t-65}$, with the corresponding cohort survival rate, if available[8], denoted as q_{it}^{15} and q_{it}^{65}, thus $B_{i,t-15}^{*} = B_{i,t-15} * q_{it}^{15}$ and $B_{i,t-65}^{*} = B_{i,t-65} * q_{it}^{65}$.

Second, the contribution of fertility to population growth, here the contribution of inflows into and outflows from the working-age population, depends on the population size at a given point in time. Put differently, the same birth cohort might contribute to population change in vastly different ways when entering and exiting working age not only due to mortality, as it may also differ substantially when the in-between change of the population size was large, e.g., due to strong migration dynamics. We account for this by dividing births by the population level one year prior to the longest lag p in the VAR. More formally, this is

$$B_{it}^{*} = \frac{B_{i,t-15}^{*} - B_{i,t-65}^{*}}{P_{i,t-(p+1)}} \tag{12}$$

Third, the model proposed in equation (5) encompasses the contribution of the natural component to overall working-age population growth. Now, in striving to isolate the structural population shock in the residuals of the population equation by using lagged births as an instrument, we essentially address those innovations in the natural component of population change that have remained unexplained by the model. Put differently, rather than resembling the natural population change component already included in the VAR, an appropriate instrument should approximate only the idiosyncratic changes of innovations in this component. To this end, before using it as an instrument, we filter B_{it}^{*} by an autoregressive structure, with π being the corresponding coefficient, by country and year fixed-effects, and by country-year dummy variables – all of this analogous to equation (5). With a corresponding notation using an asterisk, this implies:

$$B_{it}^{*} = \mu_{i}^{*} + \delta_{t}^{*} + \pi B_{i,t-1}^{*} + E^{*} X_{it} + e_{it}^{*} \tag{13}$$

Since recorded births are flow data, we use only one lag to resemble the level structure as included in the VAR. Having estimated equation (13), we compute e_{it}^{*} and define $e_{it}^{*} = z_{it}$, i.e., the residuals stemming from this filtering step serve as the instrument in our identification strategy.

Thus, in the identification step, we exploit the information from all reduced form residuals for which there are available data for births. Notably, this is the case for 90.6 percent of the observations. For the remaining 9.4 percent, estimated data exist. In Appendix

[8] Again, we document all data sources and adjustment steps in the Online Supplement in detail.

A, we outline in detail across which countries and periods these estimated data points are distributed. Importantly, while we include all observations, based on estimated or observed births data, in the filtering equation (13) – in order to the estimate the trend correctly and equivalent to the VAR structure – we rely on the subsample of the 90.6 percent observations based on actual, observed births to identify the shock.

Now, by plugging z_{it} into equation (10) and retrieving the corresponding fitted values, we are able to isolate the structural population shock in the population equation residuals from the initial reduced-form estimation, as outlined above. Notably, in this first-stage estimation, we obtain an F statistic (HAC) of 163.1, demonstrating sufficient strength. Importantly, while both components of the instrument, births lagged 15 as well as 65 years, show sufficient strength, the combination of both yields the best fit, and is also consistent with instrumenting both inflows and outflows rather than only one of those two. Using the isolated shock in the second stage, as also outlined above, we obtain θ_j^G and θ_j^D, which are the contemporaneous effects of a structural population shock on the j-th variable in the model – in times of population growth and times of population decline, respectively.

Despite the time lags of 15 and 65 years, endogeneity concerns may arise. The literature has shown that births respond to current economic conditions (Sobotka et al., 2011), and economic conditions of today also likely predict future economic conditions. Yet, we argue that this endogeneity channel does not raise concerns in our use case. On the one hand, an economic shock may change the level of births permanently, but this does not necessarily apply to its differences. As introduced in equation (12), we rely on unexplained differences in lagged births as our instrument, and the autocorrelation of this series vanishes rapidly. This supports our argument that the variation on which we are identifying is independent of past economic shocks, even if the level has changed permanently. On the other hand, the literature has shown that the length of business cycles varies across countries and time (Jordà et al., 2017), but it is, on average, substantially shorter than the time lags of births as used above.

Moreover, using information on lagged fertility as an instrument to identify demographic changes has already some precedents in the literature. Among others, Jaimovich and Siu (2009) use such data as an instrument for the age structure of the labor force and analyze corresponding effects on output volatility. Similarly, using information on survival rates has been applied as well. In a recent contribution, Maestas et al. (2023) analyze the effect of population aging on economic growth, the labor force, and productivity. To address endogeneity issues, they use data on lagged age structure as an instrument for the contemporaneous shares, weighted by corresponding survival probabilities. In this paper, we combine these existing approaches from the literature, augment them with a filtering exercise, and use the resulting series as an instrument to identify structural population shocks in the residuals of the VAR – rather than including the variable directly in our model.

4.5 Impulse response functions and bootstrapping

By stacking all θ_j^G and θ_j^D coefficients into two vectors, Θ^G and Θ^D, and using the estimated coefficient matrices from the reduced-form estimation, G and D, we are able to derive orthogonal impulse response functions and trace the effects of a structural population shock in times of population growth and in times of population decline. Importantly, by deriving orthogonal impulse response functions, we implicitly assume that the estimated system stays in the respective regime. Hence, as argued by Auerbach and Gorodnichenko (2012), the model is linear for each regime, and the corresponding impulse response functions do not depend on history (for details on impulse response functions and history dependence in the context of nonlinear multivariate models, see Koop et al. 1996).

From the impulse responses of the log level of the endogenous variables, we can derive the reactions of further ratios and variables of interest: the labor force participation rate, the employment rate in the labor force, GDP per capita, productivity, the capital stock, and, consequently, the capital-labor ratio. In Appendix B, we outline in detail how we obtain these reactions.

We construct 68 percent confidence intervals by applying recursive cross-sectional residual resampling with $5,000$ draws. Following and building upon Jentsch and Lunsford (2022), we preserve the covariance of the structural population shock, the regime weights, and the instruments by resampling them simultaneously. We choose the block length to be equal to the lag length of the model, which corresponds to a block length of three.

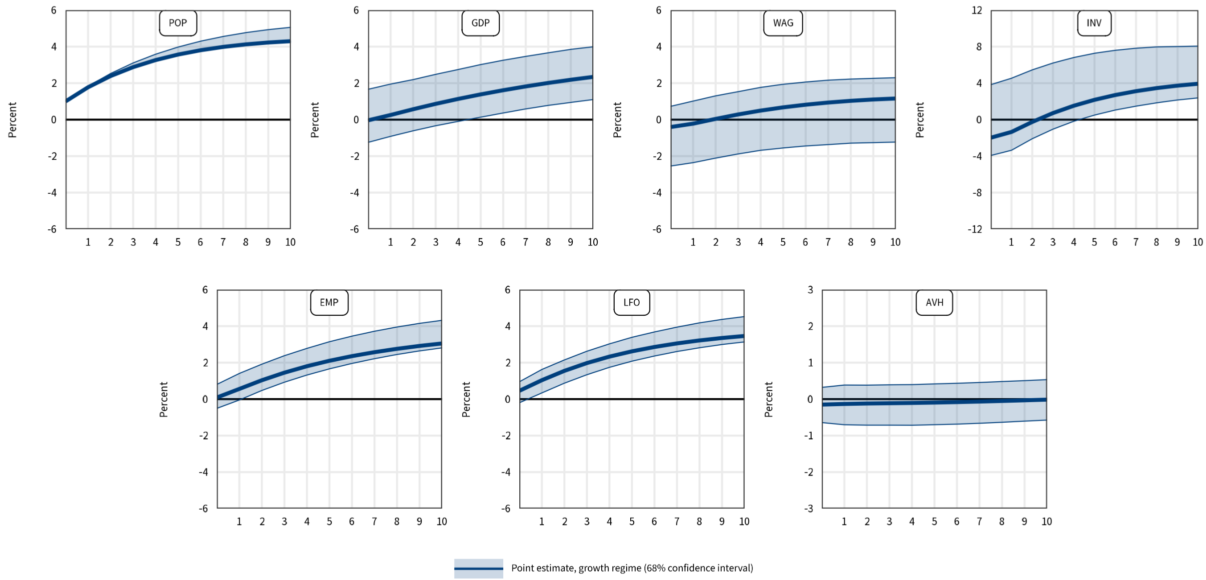
In the robustness section, we address frequent questions appearing both in panel models and historical settings, such as cross-sectional dependence or parameter constancy, and demonstrate that our findings remain valid when explicitly accounting for those factors.

5 Results

5.1 Regime-dependent effects of structural population shocks

In this subsection, we report and analyze the impulse response functions to positive, respectively, negative population shocks. Thereby, we address three varieties of (possible) asymmetries of these responses across regimes: in magnitude, in sign, and in timing. First, we present the results for the growth regime. Then, we do the same for the decline regime, and additionally include the mirrored point estimate from the growth regime. The latter enables a quick comparison in terms of symmetry; that is, what would the impulse response look like if it were symmetrical to the growth regime.

Figure 6: Impulse response functions to a positive population shock in times of growth



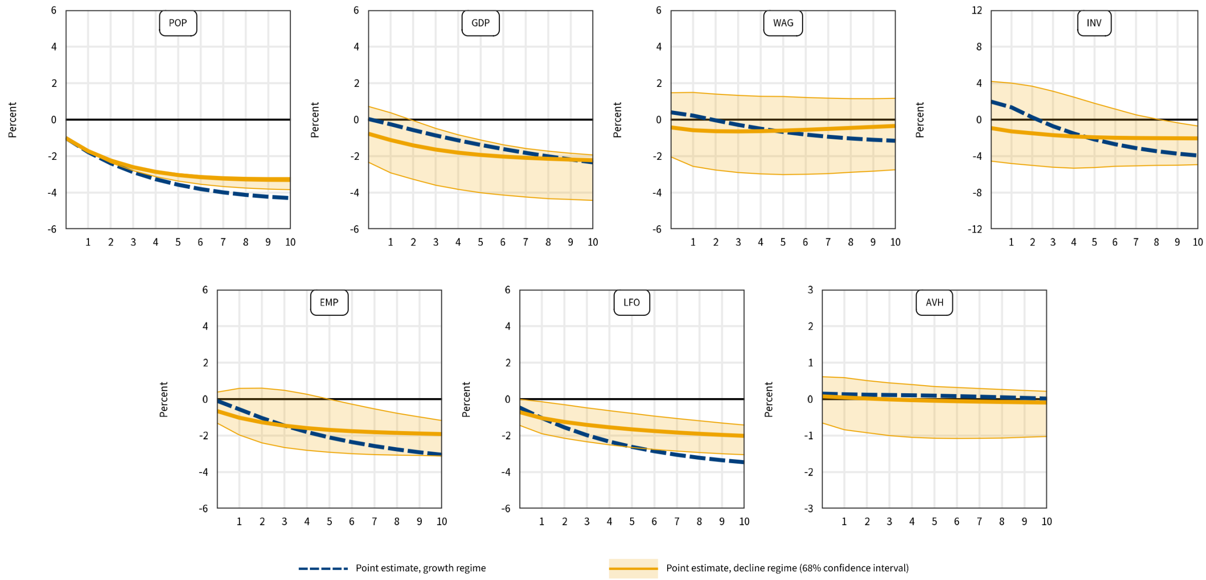
POP = working-age population, GDP = real GDP, WAG = real wages, INV = real investment, EMP = employment, LFO = labor force, AVH = average annual hours worked. Author's own calculations.

In Figure 6, the blue solid lines represent the impulse response functions of the point estimates of the level variables included in the baseline specification to a positive population shock. Since we include all variables in logs, the results can be interpreted as elasticities. Thus, the impulse response functions indicate the percent change of the respective variable to a 1 percent population shock. The blue shaded areas indicate corresponding 68 percent confidence intervals. The plots permit the analysis of the effects over a horizon of up to ten years after the shock, i.e., from the short to the medium and long term.

As Figure 6 illustrates, the impulse response of the population variable to its own shock grows by up to 4 percent after ten years. This extent is important as it sets the benchmark to which the reaction of the other variables must be compared. It mirrors that population growth is persistent.

The trajectories of the other impulse responses indicate that economic reactions to population shocks in periods of growth take time. Put differently, in periods of growth, population changes do not translate into economic reactions straightaway. However, the responses of GDP, of investment, and of the extensive margin of labor supply – employment and labor force – grow and become significant. By contrast, as the plot indicates, we do not find any significant effects on real wages or on average annual hours worked. Below, Figure 7 offers the complementary analysis for the decline regime. The solid orange line indicates the impulse response functions of the point estimates of the level variables included in the baseline specification to a negative population shock of 1 percent in times of population decline. The orange shaded areas indicate the corresponding 68 percent confidence intervals. The dashed blue line indicates the mirrored point estimate from the

Figure 7: Impulse response functions to a negative population shock in times of decline



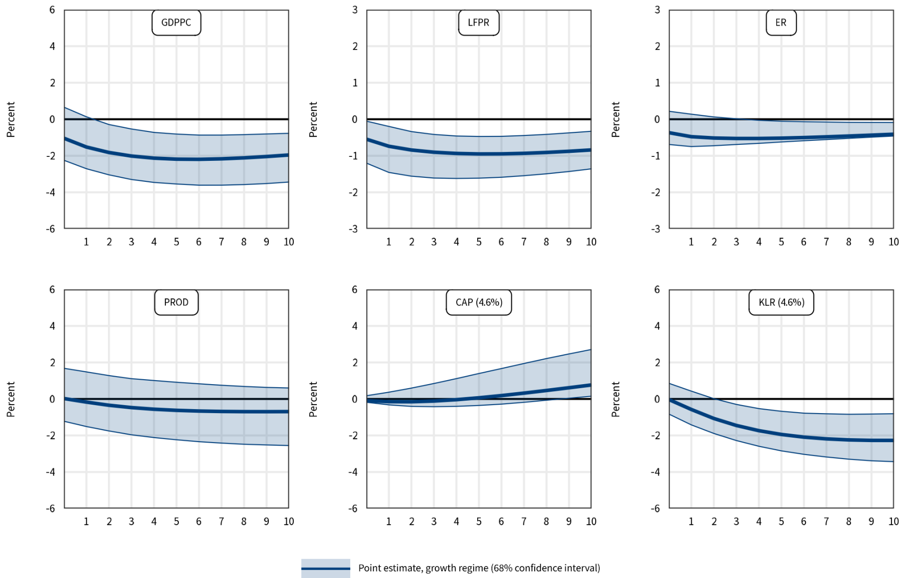
For abbreviations, see notes of Figure 6. Author's own calculations.

growth regime, as given in Figure 6.

As Figure 7 shows, the impulse response of the population variable is less pronounced in the long term compared to the growth regime, flattening out at about 3.3 percent after ten years. Again, this is the benchmark to which the other results must be compared before drawing conclusions across regimes. Contrary to the growth regime, population changes translate more swiftly into the economy in times of decline. In the short term, this becomes visible in the point estimates of GDP, investment, and employment. Unlike population growth, population decline quickly passes through to the labor market. But in the medium to long term, the initial differences disappear or reverse. The effect on total GDP after ten years is similar in both regimes. The impulse responses for investment, employment, and the labor force flatten our more quickly – both in comparison to the growth regime but also in comparison to the trajectory of the population in the decline regime. These results suggest that economies have proven to be successful in cushioning the adverse effects of population decline on labor supply. Since this avoids further losses in the production factor labor, for the complementary production factor capital it also counteracts disinvestment tendencies, as mirrored in the corresponding impulse response. As in the growth regime, we do not find any significant changes of real wages or average annual hours worked.

So far, the analysis has focused on the results as straightforwardly provided by the baseline model. By deriving a series of additional impulse response functions, we are able to quantify these results in the form of well-known indicators, such as the labor force participation rate. Below, Figures 8 and 9 allow for corresponding analyses. For the depreciation rate, we assume 4.6 percent (e.g., ECB, 2006). We discuss variations of this

Figure 8: Additional impulse response functions to a positive population shock in times of growth



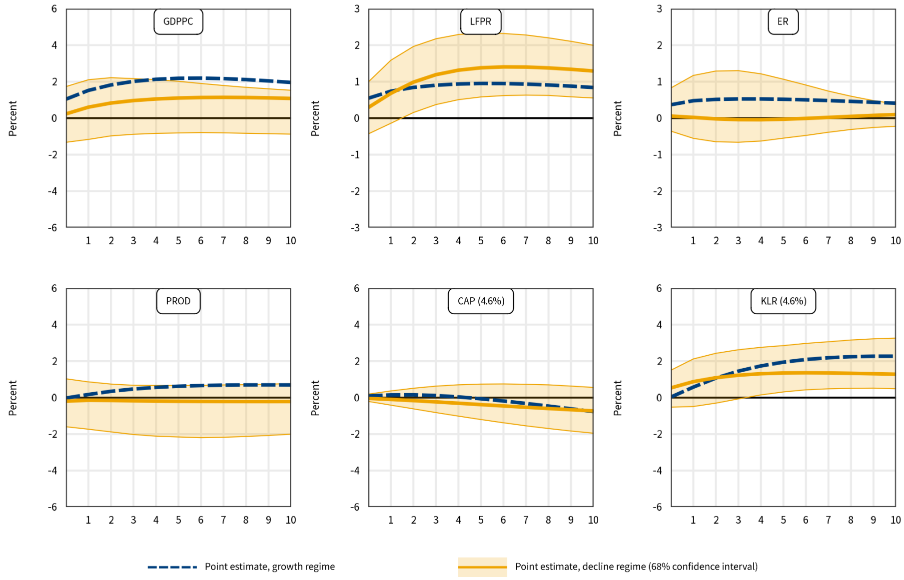
GDPPC = GDP per capita, LFPR = labor force participation rate, ER = employment rate, PROD = productivity, CAP = capital stock, KLR = capital-labor ratio. Author's own calculations.

deprecation rate in the next section. As Figure 8 shows, a positive population shock in times of population growth causes GDP per capita to decline. The point estimate of the short-term effect indicates a pronounced but insignificant decline. After ten years, the effect arrives at a significant 2 percent decline. Importantly, this impulse response is calculated using the population variable in the model, which is the working-age population. Thus, the effect should rather be interpreted as GDP per capita of those of working age. The effect on GDP per capita measured using the total population depends on the ratio of those of working age to those of non-working age and, even more importantly, on the changes in the non-working-age population following the shock. Quantifying these effects is beyond the scope of this paper.

There are two possible explanations for this decline in output per capita. One is that labor does not increase as strongly as the population; that is, proportionally fewer people contribute to production. Looking at the level effects in Figure 6, this effect appears to be evident and is quantified in Figure 8, where the labor force participation rates decline significantly, by 0.8 percent in the long term. Moreover, the employment rate in the labor force declines significantly by 0.4 percent after ten years. Put differently, following a positive population shock in times of population growth, people participate less in the labor market, and those participating are less often in employment – i.e., the unemployment rate increases.

Another possible explanation is changes in productivity. The impulse response function for productivity – output per hour worked – suggests an effect close to zero in the short term, and subsequently a moderate decline by 0.7 percent, which is, however, not sta-

Figure 9: Additional impulse response functions to a negative population shock in times of decline



For abbreviations, see notes of Figure 8. Author's own calculations.

tistically significant. A certain decrease in productivity would be explained by a lower capital-labor ratio. Indeed, the capital stock increases only with a lag. As a consequence, we observe only an incomplete adjustment of the capital side after ten years according to the results of our model – which implies a lower capital-labor ratio. In fact, in a back-of-the-envelope calculation, when assuming a stylized Cobb-Douglas production function with an output elasticity of capital of one third, an isolated change in the capital-labor ratio of –2.3 percent would reduce productivity by 0.8 percent – which is very close to the model results.

In Figure 9, the derived impulse response functions for the decline regime are visualized, again with the mirrored response from the growth regime as a dashed blue line. The increase in GDP per capita is not as pronounced as the response in the growth regime would suggest, arriving at around 1.1 percent after ten years, and not reaching statistical significance. Again, there are two possible drivers for changes in GDP per capita: increasing employment participation or productivity. In Figure 9, the regime differences in the labor supply reaction in terms of participation and employment are well illustrated. The labor force participation quickly overtakes the mirrored response from the growth regime. After ten years, we see a substantial and significant increase of the labor force participation rate in times of decline by 1.3 percent, which is about 0.5 percentage points larger compared to the mirrored response from the growth regime.

In order to dig more into the underlying processes, gender-specific results are of particular relevance. While we are not able disentangle gender-specific patterns due to data limitations in the historical context, a look on corresponding descriptive data (OECD, 2024) for more recent observations reveals participation effects for both, women and men: In decline periods, analogously to Figure 4, participation rates of females grew annually by a median of 0.5 percentage points (compared to 0.4 among all observations), and rates of males exhibited a median annual growth of 0.02 percentage points in decline periods (compared to -0.1 among all observations).

Moreover, as outlined above, in times of growth, the unemployment rate rises as the labor force grows more strongly compared to employment. But in times of decline, by contrast, we observe much more similar changes of employment and the labor force. As a result, as Figure 9 visualizes, the employment rate remains roughly stable throughout the analyzed horizon, thus we find no evidence for any significant changes in the unemployment rate in times of decline.

Eventually, while productivity declines moderately in the growth regime, we do not observe any changes in periods of population decline. But as in the growth regime, we observe only incomplete capital adjustment, leading to an increased capital-labor ratio of about 1 percent after ten years. Since productivity does not increase and neither unemployment nor hours worked change noticeably, this implies that the observed rise in GDP per capita in periods of decline is mainly driven by changes at the extensive margin, i.e., increasing labor force participation.

However, the absence of productivity effects in the decline regime despite an increasing capital-labor ratio is noteworthy. Again, in a back-of-the-envelope calculation assuming a stylized Cobb-Douglas production function and an output elasticity of capital of one third, a 1.3 percent increase in the capital-labor ratio would imply an increase of productivity by 0.4 percent. But in Figure 9, we observe even a slight decline. Consequently, there is some scope for other factors to exert negative effects on total factor productivity following a negative population shock.

5.1.1 Discussion: a view on the existing literature

One explanation may lie in the interaction of the capital stock and labor supply. If the latter decreases and, at the same time, the capital stock does not fall proportionately, we observe a rising capital-labor ratio, as outlined above. When expecting a rising capital-labor ratio to translate into higher productivity, one implicitly assumes that the additional capital per worker is fully utilized. But if capital utilization is neither exhaustive nor fixed – which is, in general, supported by empirical data (Gorodnichenko and Shapiro, 2011) – productivity effects of changes in the capital-labor ratio due to population shocks may be limited. However, when attributing the whole divergence of productivity and the capital-labor ratio in times of population decline to underutilized capital, we would assume this effect to be persistent. This would be difficult to reconcile with the literature that analyzes the crucial role of fluctuations in capital utilization in order to absorb shocks in a business cycle – i.e., short-term – perspective (e.g., Burnside and Eichenbaum, 1996).

This stresses mechanisms that are more fundamental than fluctuations at business-cycle frequency. Approaches such as Jones (2022) seek to model the endogenous dynamics leading to population decline and analyze, as a consequence of population decline, the implications for economic growth in the long run. Jones (2022) shows that in a regime of persistent population decline the diminishing number of people eventually leads to stagnating GDP per capita and productivity, as outlined above. While we do not analyze the long-run or steady-state dynamics of the economy analogously to theoretical models, the effects we are analyzing can be compared since they are conditional on the prevailing regime, i.e., on enduring population decline. Consequently, we use the way ideas evolve according to Jones (2022, see Table 1) and the calibration[9] therein in another back-of-the-envelope calculation and compare two scenarios: First, a scenario where there is a constant negative population growth rate, set to –0.5 percent, as done by Jones (2022). Second, a scenario where there is additional, exogenously induced population decline as given by the impulse response of the population from our baseline specification. By comparing the trajectories of knowledge in both cases, we observe that, compared to the first scenario, the additional population decline lowers productivity by about 0.3 percent after ten years.

Thus, the underlying mechanism as argued by Jones (2022) – fewer people produce fewer ideas, which exerts a negative effect on total factor productivity – is consistent with our findings. This applies to both the conceptual perspective but also to the attributed size effect (0.3 percent compared to 0.4 percent according to our model). Notwithstanding, in our model we find an increase rather than stagnation in GDP per capita in Figure 9 – which is explained by the combination of rising capital intensity and rising labor force participation. These mechanisms, that are absent in standard models, jointly offset possibly negative productivity effects due to a decreasing population size. Logically, these margins should be part of theoretical considerations on the odds of GDP stagnation.

Other results discussed above have yet not been addressed explicitly in the context of population decline, but in the related literature. An established strand analyzes the wage and unemployment effects of shrinking cohort sizes. Another strand investigates the effects of emigration. If flexibility of labor demand is limited, shrinking cohort sizes may decrease crowding out effects and thus improve the labor market outcomes (Easterlin, 1961). However, for firms, smaller youth entry cohorts may also lower the incentive to create new jobs (Shimer, 2001), besides labor supply also aggregate demand effects have to be taken into account (Macunovich, 1999) and the cohort effects may change over time (Zimmermann, 1991). Similarly, other studies have found that emigration may increase the wages of stayers (e.g., Biavaschi, 2013; Dustmann et al., 2015). While the overall evidence is not unambiguous, even if one comes from the hypothesis that labor market

[9] Jones assumes 2 percent annual TFP growth. This calibration suits our empirical data well, as we observe a median annual productivity change of 2.2 percent (only years that entered the estimation).

outcomes deteriorate with cohort size (such as Berger, 1985; Brunello, 2010; Foote, 2007; Garloff et al., 2013) or are linked to emigration, the view of our study differs in one important aspect: the cohort shifts and emigration dynamics in the recent decades analyzed in the literature usually do not represent actual (working-age) population shrinkage, which is our focus. Evidently, the overall decline of the working-age population goes beyond cohort shrinkage or emigration, and thus we find distinct adjustment channels: no wage and unemployment reaction, but higher labor force participation and capital deepening. Importantly, rising participation does not come about through wage increases, as would be the case when thinking of conventional labor supply elasticities. Evidently, contraction in the labor market affects the extensive margin directly via other channels.

5.1.2 Limitations: historical context and data quality

Breaking new ground with historical and comparative datasets is subject to a trade-off between the value of additional insights and measurement uncertainty. While we are confident that our investments in data quality are enough for the former to outweigh the latter, results and conclusions are subject to limitations. First and foremost, this can be attributed to the historicity of the data used. Both the quality of measurement of labor market indicators as well as underlying concepts and definitions (see, e.g., Romer 1986 or Piore 1987) have changed over time, which complicates, for example, the comparison of unemployment dynamics between the late 19th and the early 21st century. Moreover, for example, one key limitation in interpreting the absence of effects on wages is the data quality: Most historical wage series focus on urban unskilled laborers. In the literature, some argue that these wage series resemble overall wages in the economy quite well (e.g., Allen, 2001). Still, given that urban unskilled laborers have represented only one part of the labor force, there are conceivable limitations in the interpretation.

Similarly, overall economic and social structures have changed. Put differently, economies and their labor markets have evolved strongly over the past 140 years, for example with regard to sectoral structure (among others, Herrendorf et al., 2014) or, in recent decades, due to automation (Carbonero et al., 2020) – and the same applies to social norms and values (e.g., Fernández, 2013; Humphries and Sarasúa, 2012). While our dataset offers clear advantages for estimating effects that would otherwise be hard to measure, it is, due to the long time span, also subject to such transformations. We address potential interference of these changes over time for our estimation results in the upcoming robustness section.

Eventually, the external validity of our study is naturally linked to the range of population decline rates as observed in the past. As insights from theoretical models indicate (e.g., Sasaki, 2023), the size of population decline might also play a role. The median of the decline observations in the sample is –0.26 percent, with an interquartile range from –0.45 to –0.10 percent, and with only few observations exceeding the –1 percent threshold

(Figure 2). The value of –0.26 percent is close to the median of the projected annual changes in the aggregate of advanced economies until 2040, as mentioned above. Still, there are countries where the projection suggests the median of the annual changes to be close to or even exceeding –1 percent (e.g., Italy, Japan, or Germany). Given the insights from theory, such divergence must be considered when linking population projections to the results and conclusions presented in our paper.

5.2 Robustness

We check the plausibility of our results by applying a series of robustness checks, thereby addressing apparent and frequently discussed factors we haven't explicitly accounted for in our baseline specification. In each case, the corresponding plots can be found in the Online Appendix.

First, the data underlying our estimation covers a long period in which large-scale social, technological, and economic changes have occurred. This raises questions as to whether the "nature" of macroeconomic interdependencies might have changed over time and, as a consequence, questions the parameter **constancy assumption** embodied in our baseline specification. We use a straightforward approach to demonstrate the robustness of our findings by splitting the sample in 1950, which is the first post-war observation, and estimating a separate linear model for 1950–2019.[10] The results are shown in Figure 12. The trajectories of the derived impulse responses are remarkably similar for both samples, with remaining differences mostly stemming from contemporaneous effects. Based upon this analysis, we argue that the assumption of parameter constancy is reasonable, thus our results appear to be robust.

Second, in a similar vein, social, technological, and economic differences do not only exist in time, but also across countries. In the case of migration, for example, the strongly changing patterns for the countries in our panel are well documented - over the course of the past 140 years as well as between countries (Ferrie and Hatton, 2013). In the baseline model, we account for time-invariant unobserved heterogeneity by the inclusion of μ_i. Now, we evaluate whether our model is also robust to the inclusion of **country-specific trends**. We allow for the changes in trends by including separate country-specific trends for the pre-war (linear), the interwar (linear), as well as the post-war period (logarithmic). The functional form of the time trends was chosen after visual inspection of the data, which is supported by fit measures. Figures 13 and 14 display the impulse responses that resemble the baseline findings in most cases. This is reassuring in view of the high flexibility of deterministics that we allowed for. A moderate deviation is given by the flat GDP per capita response in times of decline, compared to an insignificant increase in the baseline. This is connected to a somewhat weaker capital response.

[10] Estimating nonlinear models for these subsamples is not feasible due to the lack of a sufficient number of decline observations.

Third, advanced economies, and thus their labor markets, are anything but entities independent from each other – a fact that necessarily needs to be accounted for in a given empirical strategy. However, as argued by Pedroni (1999) and others, a common way to account for **cross-sectional dependence** is to demean over the cross-section, as done by introducing δ_t in the estimation above. Another way to account for cross-sectional dependence, and in doing so a robustness check, is to introduce an additional continuous regressor, such as world GDP (less a country's own; e.g., Comunale 2022). We test the robustness of our specification accordingly, calculating world GDP from GDP per capita and population data from Bolt and van Zanden (2020), and include the growth rate of the contemporaneous period as an exogenous predictor. The corresponding Figures 15 and 16 can be found in the Online Appendix. For both regimes, the impulse responses are very similar to those of the baseline specification.

Similarly, populations across countries are not independent from each other, but connected by migration flows. This raises the question of another adjustment channel: When a country enters population decline, the adverse consequences may be mitigated by increasing immigration from other countries. Yet, this mitigation potential may vanish if these sending countries enter population decline as well. Again, we check the robustness of our findings accordingly, here by including the growth rate of the aggregate working-age population of all other countries in our sample. Figures 17 and 18 display the results, which are also very similar to the baseline. Based upon these findings, we conclude that our results are robust in terms of unaccounted cross-sectional dependence.

Fourth, in distributing growth and decline probabilities across the panel, we imposed **parameter assumptions** on the transition function. In order to investigate whether imposing different assumptions alters our results, we conduct two robustness checks. First, rather than assuming $\kappa = Q_1^{POP,G,z}$, we set $\kappa = Q_1^{POP,z}$, which is the lower quartile across all observations, growth and decline, and corresponds to a value of 0.38 percent. The corresponding Figures 19 and 20 can be found in the Online Appendix. While the results for the growth regime for this robustness check are very similar to those of the baseline specification, the decline regime shows some differences. While the findings for the labor force participation rate are robust, the robustness check suggests a slight increase in unemployment. However, the confidence interval of the baseline specification is wide. Moreover, the robustness check suggests some differences in productivity, possibly driven by a longer-lasting increase in the capital-labor ratio. Nevertheless, the main results, that the labor supply reaction is more pronounced compared to the growth regime as well as a different effect on unemployment in the long run, still hold. Second, rather than using $\lambda = 100$, we impose $\lambda = 200$ in order to evaluate the effect of using a different smoothing parameter. Figures 21 and 22 display the corresponding results, which show only minor differences to the baseline results. Overall, these results indicate robustness towards potential misspecification of the transition function.

Fifth, the effects of **population ageing** on the economy and the labor market have already drawn widespread attention in the literature (among many: Acemoglu and Restrepo, 2017; Aksoy et al., 2019; Börsch-Supan, 2008). In our baseline specification, we do not explicitly control for any age structure underlying the included working-age population. However, since we include year effects in our baseline specification and changes in the age structure exhibit strong similarities across advanced economies (see, e.g., Reher 2015 for a discussion on population ageing across countries due to *baby booms* and *busts*), we argue that most of these effects have already been captured. Still, to strengthen our argumentation and to account for possible effects stemming from country-specific variations in demographic trends such as boom and bust cycles, we conduct another robustness check by explicitly including information on age structure. Following Aksoy et al. (2019), we include contemporaneous shares of age groups as exogenous predictors.[11] The corresponding Figures 23 and 24 can be found in the Online Appendix. The results show only very slight differences compared to the baseline specification. This confirms the expectation that age structure effects are no important disregarded factor.

Eventually, we evaluate the sensitivity of the results for the capital-labor ratio to **changed depreciation rates** by assuming lower (2.5 percent) and higher (7 percent) values. We find these comparison values by following the assumptions of Xiao et al. (2021) for depreciation rates over time in low- and high-income countries. In Figure 25, we visualize the effects for both the growth and the decline regime simultaneously. The comparison of the results from the point estimates indicate only minor differences – with more pronounced changes for the 2.5 percent depreciation rate and less pronounced effects for the 7 percent depreciation rate case. But importantly, in the case of the 7 percent depreciation rate, only some intermediate years in both regimes indicate significant effects, the long-run effect is insignificant. Thus, the sensitivity analysis demonstrates that the significance of the effects of population changes on the capital-labor ratio are dependent upon the assumed depreciation rate. Put differently, the finding on significant long-run changes in the capital-labor ratio as a consequence of population shocks does not necessarily hold. Still, the point estimates suggest large effects, irrespective of the assumed depreciation rate.

6 Conclusion

According to recent projections, most advanced economies will face population decline in the years and decades to come, providing a challenging demographic context in the

[11]Yet, as we are using lagged births as instruments, we already account for the implied change in the age structure due to inflows and outflows. To address the corresponding endogeneity issue, we include the shares of ten-year age groups among those aged 20–59 years as a proxy. In doing so, we only include information on age structure that is independent of inflows and outflows due to lagged births – and control for the effects of the accompanying heterogeneity.

short to the medium and long term. Notably, decline patterns are expected to be particularly pronounced among those of a working age. Although a decreasing population may have profound economic implications, above all in the labor market, there is still little theoretical and empirical evidence on this issue. We contribute to this sparse body of literature by focusing on the latter and compile a new historical dataset using more than 100 individual sources, containing information on demographics (population, births, mortality) and labor market variables (real GDP, real investment, real wages, employment, unemployment, participation rates, hours worked) to analyze the labor market effects of population decline from a macroeconomic point of view.

Notably, this research objective does not only call for combining information from several countries, but identifying causal effects of population changes and differentiating between times of demographic growth and decline. Tailoring our modelling approach to these requirements, we combine a reduced form panel model with an instrumental variable approach and a smooth transition specification. We identify structural population shocks in the reduced form residuals using lagged births as external instruments for working-age population inflows and outflows, and derive regime-dependent orthogonal impulse response functions to trace the effects of positive (negative) population shocks in the labor market in times of population growth (decline).

So far, the existing literature has relied on theoretical models to analyze the economic effects of population decline. Empirically, the effects have, as yet, been unclear, and our paper has addressed this gap. The results resemble the conclusion that maintaining economic growth is generally feasible and add additional insights: We find that population changes pass through to the labor market more quickly in times of decline compared to times of growth. Subsequently, regime-dependent adjustment processes unfold. Labor force participation increases as a response to the decline in labor supply, and in the long term it does so more strongly than it shrinks in times of growth. This rise in overall labor force participation likely plays a crucial role for further observed patterns, for example in decelerating initially swift disinvestment tendencies in times of population decline. By contrast, we find no significant changes in the unemployment rate as a response to population decline. Similarly, despite declining labor supply, we do not find any significant changes of wages as a shortage indicator over time. Eventually, while both our results and the existing economic literature on population decline point to negative effects on productivity, the findings of this paper suggest that corresponding negative effects for economic growth are mitigated by increases in participation and the capital-labor ratio.

Thus, the paper suggests that incorporating elastic labor supply into future model-based approaches that analyze the effects of population decline may enhance the resulting insights. Importantly, two properties should be considered: First, increases in participation are limited, eventually by the population size. Second, adjustments along the participation dimension may take time, as our results suggest. Similar results exist for other interventions. For example, there is evidence that active labor market policies (ALMPs) increase labor force participation rates (Escudero, 2018) – but short-term effects of ALMPs are substantially smaller than medium- to long-term effects (Card et al. 2018 for ALMPs targeting persons inside the labor force).

Furthermore, and despite some caveats for the interpretation of the results as discussed in section 5, the paper offers additional contributions, both to the academic literature as well as in a broader policy perspective. Regarding the academic literature, the further contribution is threefold: Data relatedly, the paper offers a (partially) novel compilation of historical labor market data, providing both a suitable database for future research projects as well as a suitable starting point to improve existing, or create new, historical datasets. Methodically, it expands the existing body of literature by combining a proxy SVAR identification strategy with a nonlinear reduced form panel model. Substantively, it proposes to use, and implements, lagged births as a suitable instrument for the identification of population shocks. Jointly, these contributions permit, for the first time, the conducting of a comprehensive empirical analysis of the labor market effects of population decline from a macroeconomic perspective.

However, also in the broader policy context, the results bear importance. In light of the imminent population decline across advanced economies and corresponding discussions concerning labor supply shortages, findings such as increasing labor force participation in response to population decline are of crucial importance – and indicate that adjustments are feasible. This point must be qualified in its translation into policy. Clearly, the activation of individuals outside of the labor force is limited beyond a certain point; this applies, in particular, to demographic groups that already exhibit high participation rates. Therefore, adjustment is likely to become more critical the more the existing potential is exhausted. Furthermore, the systematic responses to demographic shocks as measured in the model based on empirical data include the political reactions that have appeared in the past. Therefore, if policymakers want to change the outcome, their measures would have to go beyond the typical reactions of the past.

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Conflict of interest

The authors declare that there is no conflict of interest.

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A Appendix: Excluded Observations

As outlined in the main text, we exclude a number of observations from the identification of the structural population shock. In the table below, we provide information on the country, period, and reason for each case. Additionally, we also indicate how many observations are effectively lost – i.e., have not already been excluded due to, e.g., being a war year.

Table 2: Descriptive overview of the excluded observations in the identification procedure

Country	Years	Reason	No. of obs. excl.
AUS	1900-1916	For this period, only estimated annual data from Gapminder (2015b) is available for outflows.	12
AUT	1954-1955	The inflows in this period are strongly driven by the unprecedented increase in births in Austria following the annexation ("Anschluss") by Germany in 1939. We categorize these observations as outliers.	2
AUT	2004-2005	The outflows in this period are strongly driven by the unprecedented increase in births in Austria following the annexation ("Anschluss") by Germany in 1939. We categorize these observations as outliers.	2
DEU	1875-1883	For this period, only estimated annual data from Gapminder (2015b) is available for outflows.	7
GBR	1875-1907	As above, Gapminder (2015b).	31
ITA	1900-1928	As above, Gapminder (2015b).	18
JPN	1900-1939	As above, Gapminder (2015b).	18
JPN	1959-1963	As above, Gapminder (2015b).	5
JPN	2009-2013	As above, Gapminder (2015b).	5
NZL	1900-1921	As above, Gapminder (2015b).	12
USA	1900-1921	As above, Gapminder (2015b).	37

Author's own calculations. For information on data sources, see the Online Supplement.

B Appendix: Additional IRFs

With our econometric strategy, we are able to compute impulse response functions to a structural population shock for each of the seven endogenous variables in our model. Moreover, we may obtain the impulse response functions to an additional series of relevant labor market indicators, as reported in Figures 8 and 9 in section 5 of the main text, by linking the coefficients of the main results (Figures 6 and 7) to each other. Below, a detailed outline of the calculation of each of these additional impulse response functions is given.

Let GDP_t and POP_t be the estimated elasticities of a structural population shock on real GDP and on the working-age population at time t. Then, the elasticity for GDP per capita in the same period, $GDPpc_t$, is given by

$$GDPpc_{it} = GDP_t - POP_t \tag{14}$$

Let LF_t be the estimated elasticity of a structural population shock on the labor force at time t. Then, the elasticity for the labor force participation rate in the same period, $LFPR_t$, is given by

$$LFPR_{it} = LF_t - POP_t \tag{15}$$

Let EMP_t be the estimated elasticity of a structural population shock on employment at time t. Then, the elasticity for the employment rate in the labor force in the same period, ER_t, is given by

$$ER_{it} = EMP_t - LF_t \tag{16}$$

Let AVH_t be the estimated elasticity of a structural population shock on average hours worked at time t. Then, the elasticity for productivity in the same period, $PROD_t$, is given by

$$PROD_{it} = GDP_t - (EMP_t + AVH_t) \tag{17}$$

Let $INVEST_0$ be the estimated elasticity of a structural population shock on investment in period 0 and let ϑ be the annual depreciation rate. Departing from a steady-state assumption, that is, in the absence of the structural population shock there would be no changes in the variables under consideration, then the ratio of annual investment to the capital stock is equal to ϑ. This assumption allows the derivation of the contemporaneous effect of a structural population shock on the capital stock, CAP_0, as

$$CAP_0 = INVEST_0 * \vartheta \tag{18}$$

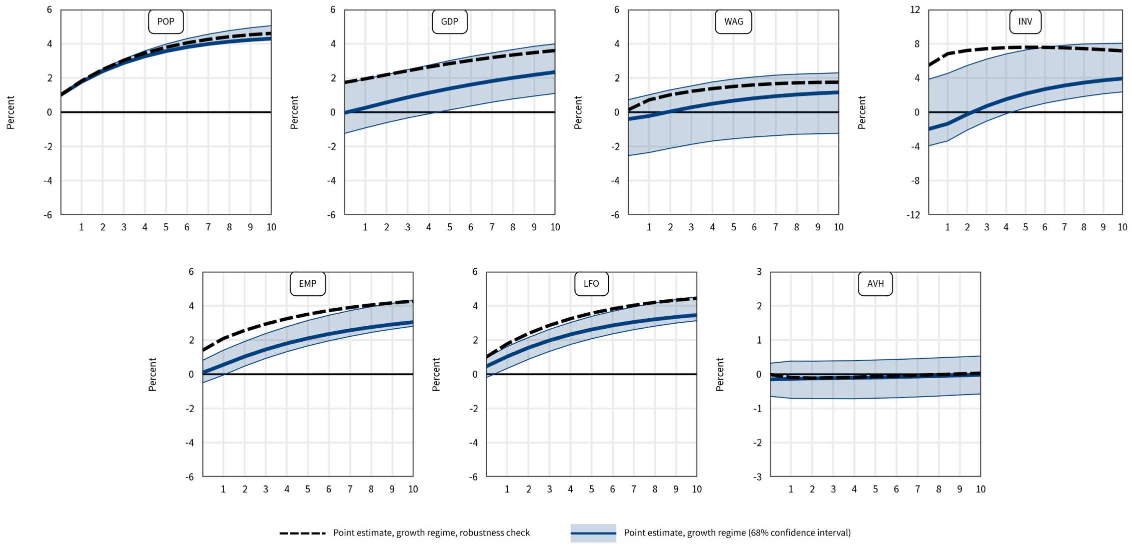
Subsequently, from period t onwards, with in this case $t = 1, \ldots, H$, and H is equal to the chosen horizon length for computing the impulse response functions, the effect is given by

$$CAP_t = CAP_{t-1} - CAP_{t-1} * \vartheta + INVEST_t * \vartheta \tag{19}$$

Eventually, the elasticity for the capital-labor ratio at time t, KLR_t, is given by

$$KLR_t = CAP_t - (EMP_t + AVH_t) \tag{20}$$

Figure 10: Robustness check for identification of contemporaneous effects, growth regime

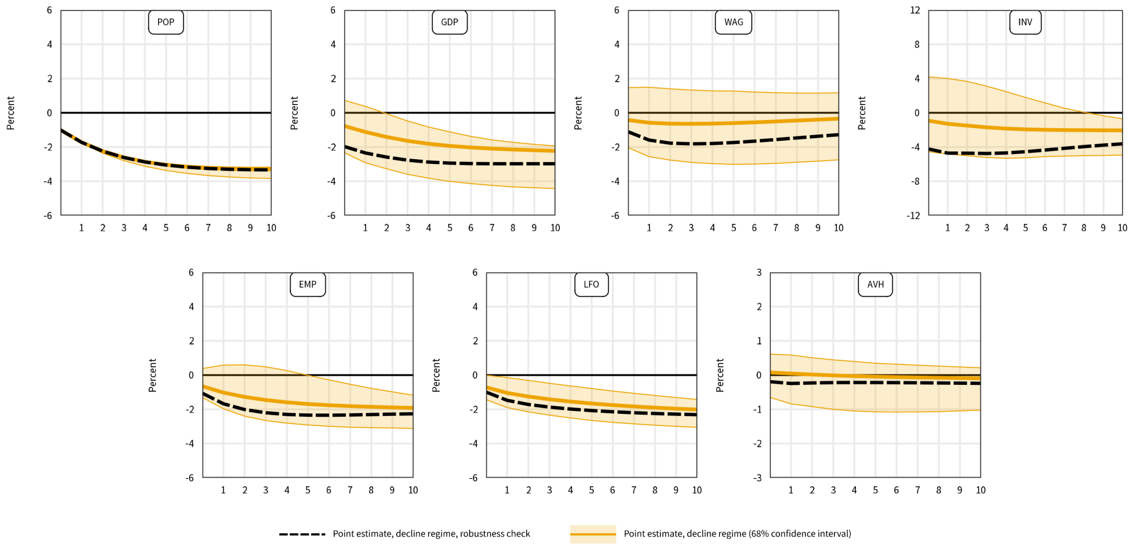


For abbreviations, see notes of Figure 6. Author's own calculations.

C Appendix: Identification

The identification of structural population shocks is of key importance for our analysis. We do this in order to ensure that we estimate the causal effect of a population change and avoid biased results due to endogeneity. Possible sources of bias range from GDP and wages to employment, among others, all of which can be assumed to possibly exert effects on population, for example as push and pull factors driving migration dynamics. Below, we illustrate the results of an identification without instruments. We follow the common identification strategy and impose a lower triangular matrix. In doing so, we assume that the population shock affects all variables in the model in the same period, but not vice versa. We implement the identification of regime-dependent shocks by regressing the residuals of each equation on the residuals of the population equation, weighted by the corresponding regime probabilities. Figure 10 and Figure 11 visualize the results of this specification. As illustrated, this identification strategy appears to capture an additional correlation between population and the other variables in the model. In particular, for GDP, employment, and investment we see far-stronger contemporaneous effects. As noted above, observing an additional strong correlation between population and these variables is consistent with typical push-pull frameworks. Particularly, given that reverse causality of economic variables on population is positive, the figures display exactly the bias one would have expected when ignoring simultaneity. Moreover, as an example, the supposedly strong effects of population on GDP cannot necessarily be reconciled with existing evidence (e.g., Headey and Hodge, 2009). Thus, the results based solely on a lower triangular matrix in comparison to our baseline results underpin the need for an instrument-based identification strategy.

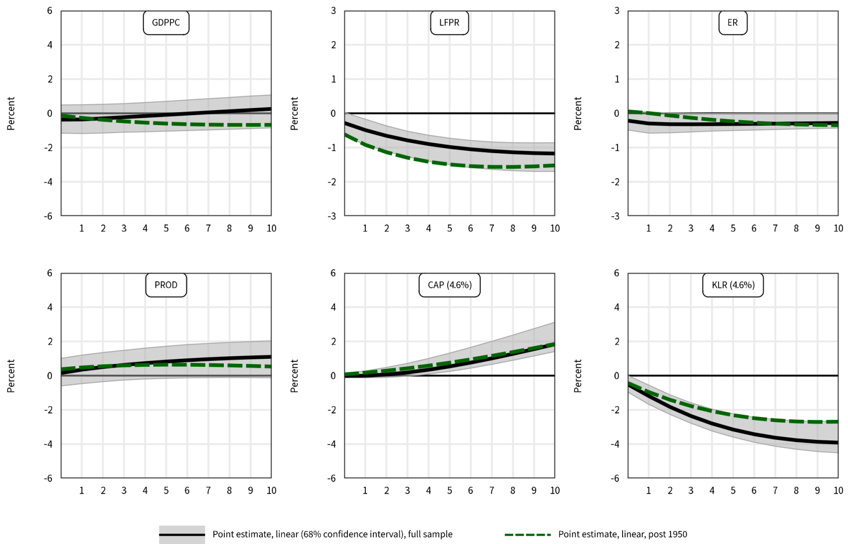
Figure 11: Robustness check for identification of contemporaneous effects, decline regime



For abbreviations, see notes of Figure 6. Author's own calculations.

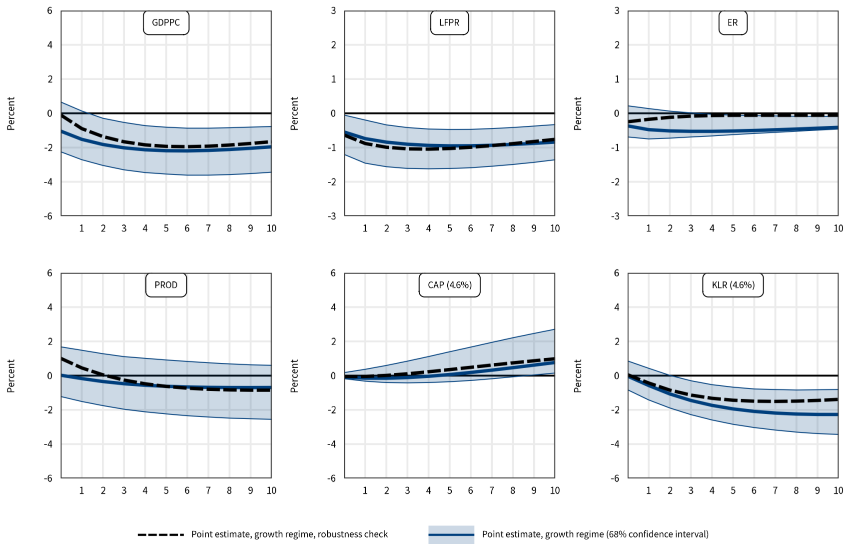
D Appendix: Robustness

Figure 12: Robustness check for parameter constancy, post-1950 vs. full sample



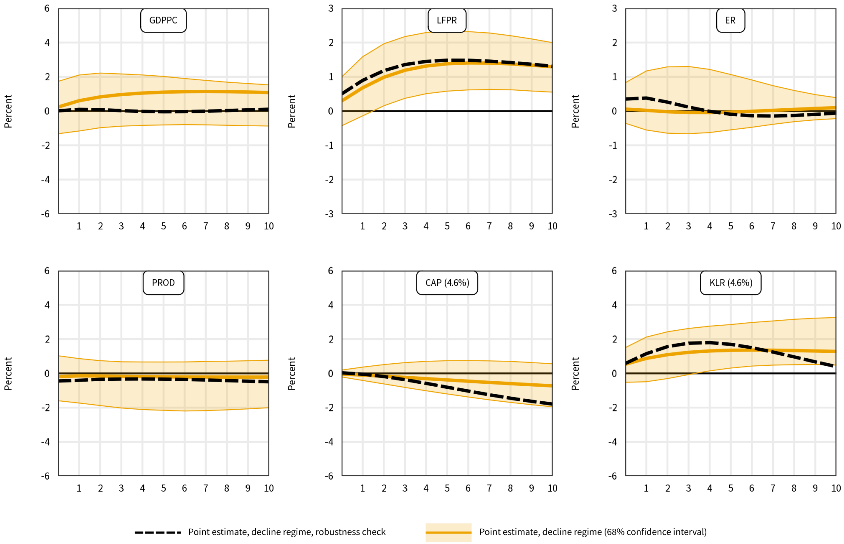
For abbreviations, see notes of Figure 6. Author's own calculations.

Figure 13: Robustness check for the inclusion of country-specific trends, growth regime



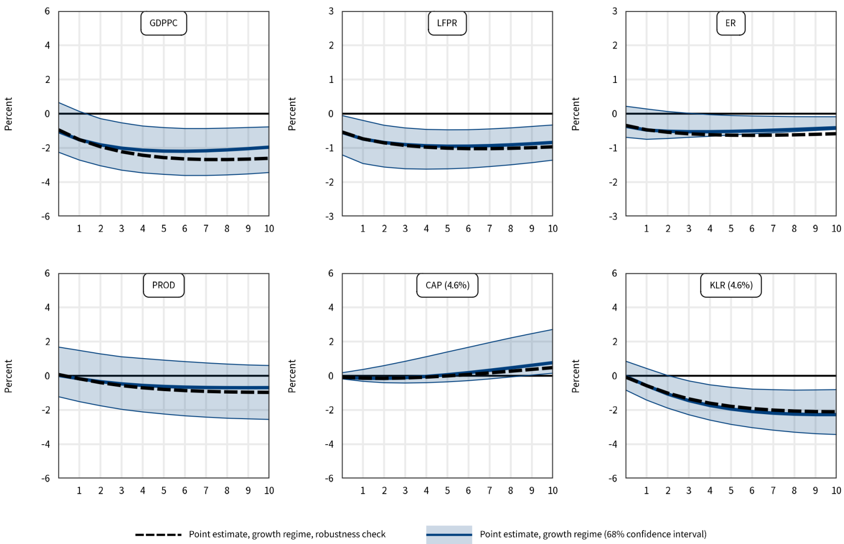
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 14: Robustness check for the inclusion of country-specific trends, decline regime



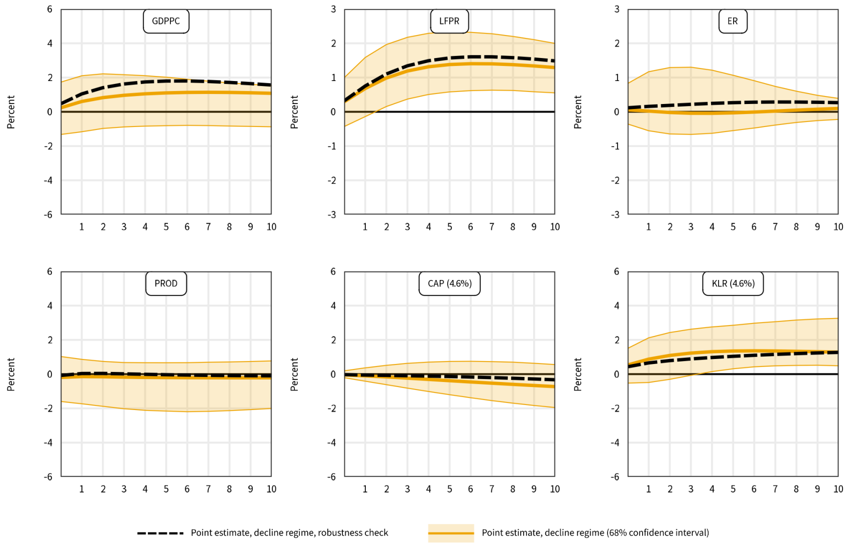
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 15: Robustness check for cross-sectional dependence (world GDP), growth regime



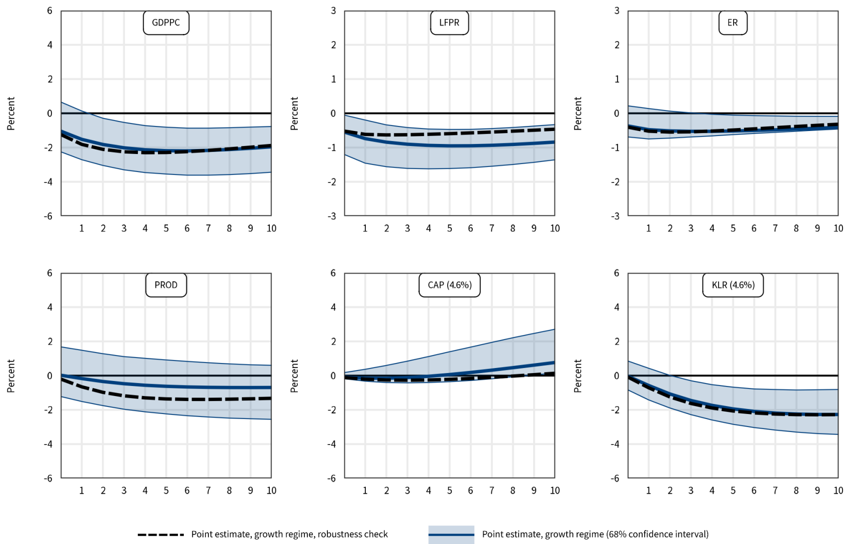
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 16: Robustness check for cross-sectional dependence (world GDP, decline regime



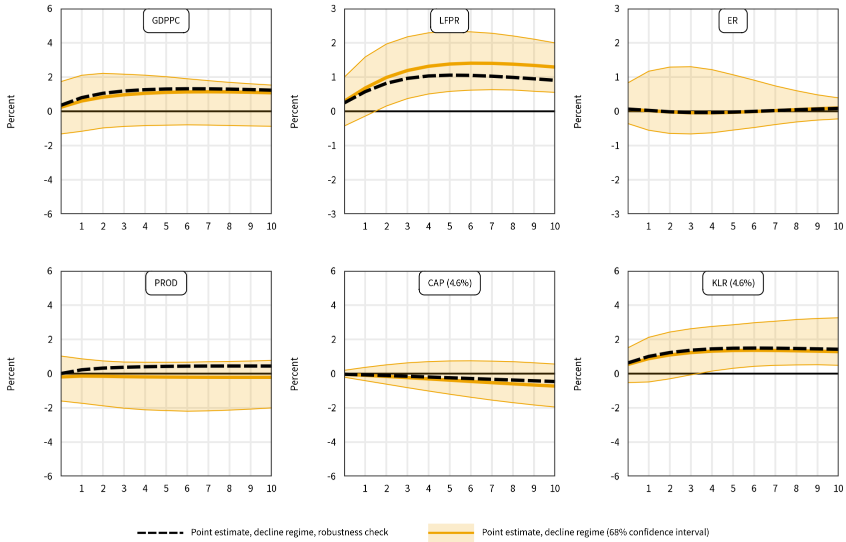
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 17: Robustness check for cross-sectional dependence (world population), growth regime



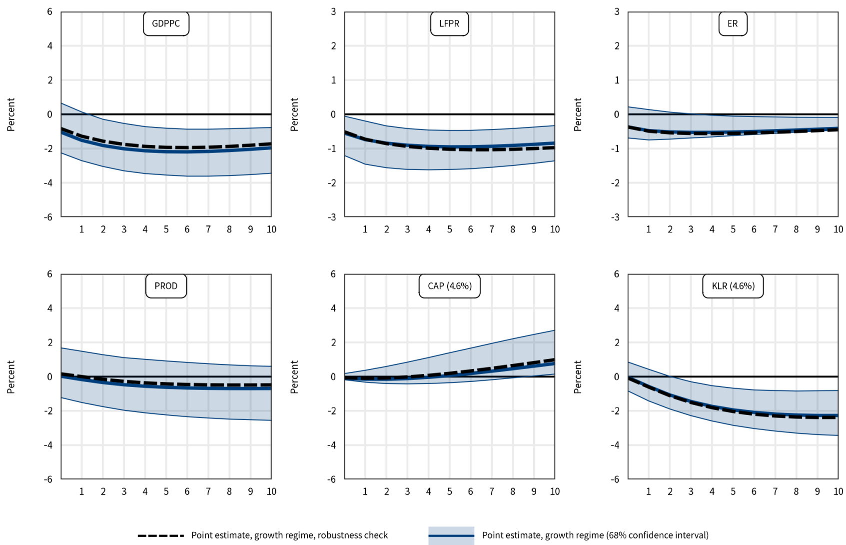
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 18: Robustness check for cross-sectional dependence (world population), decline regime



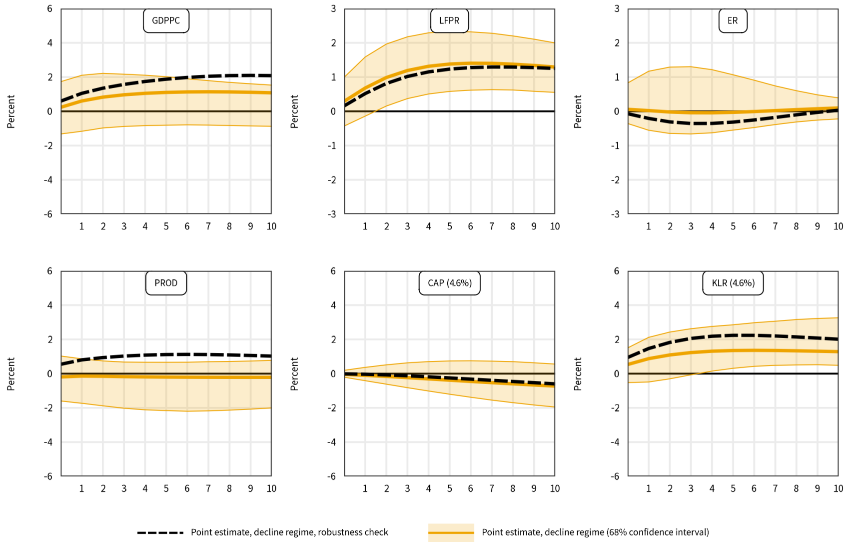
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 19: Robustness check for the specification of the transition function, growth regime



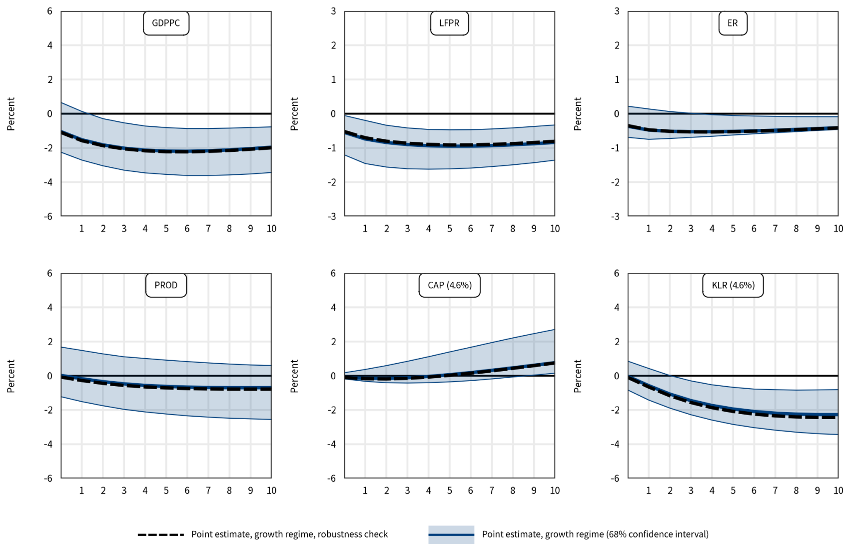
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 20: Robustness check for the specification of the transition function, decline regime



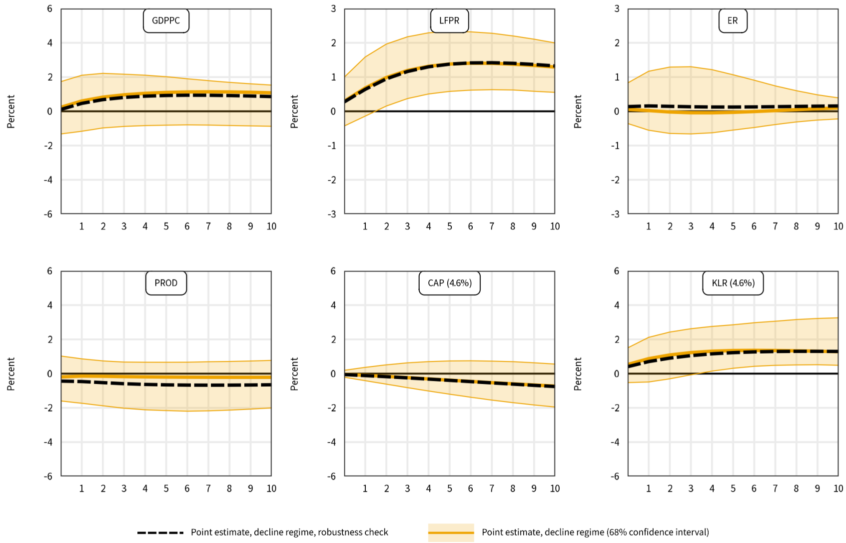
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 21: Robustness check for using a different smoothing parameter, growth regime



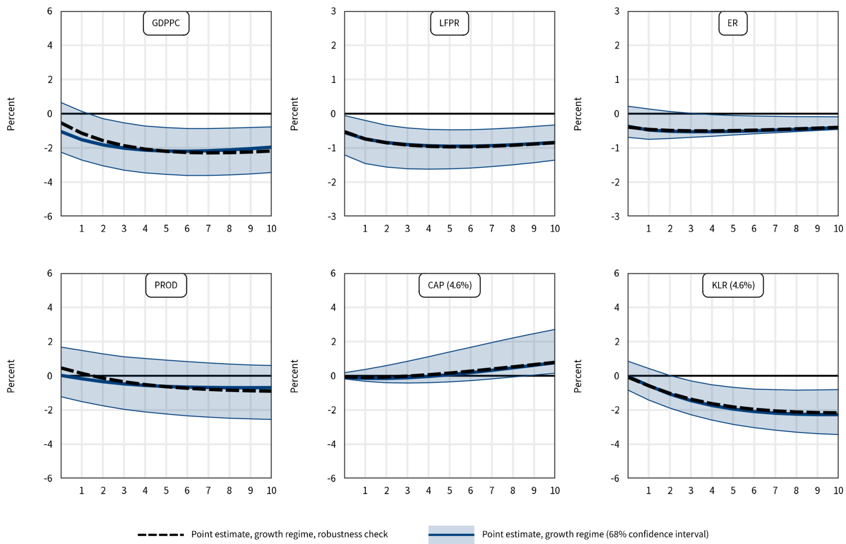
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 22: Robustness check for using a different smoothing parameter, decline regime



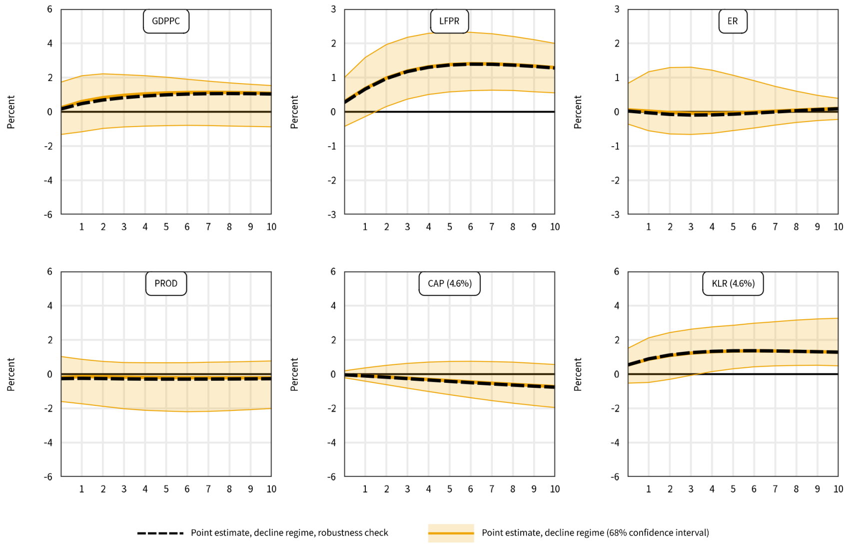
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 23: Robustness check for the impact of the age structure, growth regime



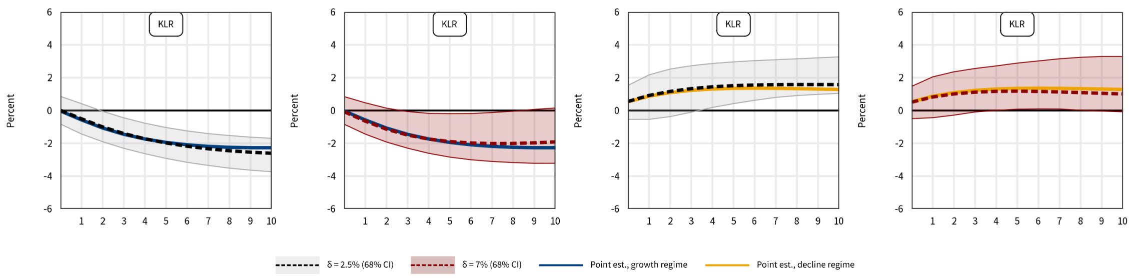
For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 24: Robustness check for the impact of the age structure, decline regime



For abbreviations, see notes of Figure 8. Author's own calculations.

Figure 25: Regime-dependent effects of varying assumption on the depreciation rate of the capital stock



For abbreviations, see notes of Figure 8. Author's own calculations.