The infrastructure dividend:
Conceptualising and quantifying the cost of providing capacity for additional people.

Jane N. O'Sullivan
School of Agriculture and Food Sciences, The University of Queensland, St Lucia Qld 4072.
j.osullivan@uq.edu.au

Abstract

The cost of providing physical capital for additional people has been largely neglected as an impact of population growth due to the lack of precise quantification of the burden. This paper discusses the application of a novel technique, which has been used to quantify the burden for Australia and the UK, to rapidly growing nations in sub-Saharan Africa. By estimating the turnover rate of different classes of assets, the actual expenditure on durable assets (infrastructure, equipment and higher level training) may be attributed to either turnover or expansion of capacity. Requiring around 6.5-7% of GDP per 1% population growth rate, expansion is a debilitating drain on the saving capacity of rapidly growing nations. Its alleviation through fertility reduction constitutes the "infrastructure dividend," which supplements and may surpass the demographic dividend in stimulating economic development. These insights encourage a re-evaluation of the role of population growth reduction in economic development.

Introduction

The 'demographic dividend' of a high proportion of working age people, enjoyed by countries with a recently reduced birth rate, has been well described and attributed a large share of the economic stimulus observed following fertility decline (Bloom and Williamson 1998, Canning et al. 2015). The 'infrastructure dividend' is less well appreciated. It arises from alleviating the need to acquire additional infrastructure, equipment and professional service providers to extend the existing quality of life and employment opportunities to additional people. It is likely to have a greater and more sustained impact on development stimulus than the demographic dividend – indeed, it operates equally in 'ageing' countries past their nadir of dependency, and even benefits declining populations.

Sauvy (1958) first attempted to calculate what he termed the 'demographic investment' required to provide physical capital for additional people. This represents a substantial call on the limited saving capacity of rapidly growing developing countries. It is inevitably the first call on these funds, at considerable opportunity cost, preventing expenditure which would increase the capital/labour ratio and the quality of services delivered. Robinson (1974) applied Sauvy's concept to the budget for Bangladesh's first five-year plan. He concluded that the cost of 'standing still' at the prevailing 3% per annum population growth represented around 75% of all the investment. With the planned level of investment, incomes might be raised by 30% over 20 years, but if population growth were at the European level (0.45% p.a. at that time) an income increase of 150% would be expected.

More recent discourse has referred to 'demographic investment' as 'capital widening' in contrast to 'capital deepening' of improving the provision per person. However, since these

early works, there has been little attempt to quantify this impost and its impact on economic development. Sauvy's work is less remembered than that of Solow (1956) who framed physical capital more narrowly as a production factor, treated as dilution of capital stock by the growth in number of workers. This is more amenable to factorisation in economic simulations (such as Ashraf et al. 2013) but these have not adequately dealt with the impact of expenditure diversion on other factors such as human capital, nor the complex system failures resulting from chronic failure to keep pace with population growth.

This paper outlines a new conceptual framework that allows the cost of capacity expansion to be measured, at least in countries with reasonably thorough economic data collection. It then discusses the potential and challenges for application of this concept to developing economies in Africa. New evidence for the scale of population growth's drag on development is presented, which suggests that the infrastructure dividend has been vital to development.

The cost of 'capital widening'

The quality of life that a nation may provide for its citizens depends greatly on its stock of durable man-made assets, in addition to its endowment of natural assets. Man-made assets include all forms of infrastructure, from private housing, industrial and commercial structures to hospitals, utilities, transport and public amenity. In addition, they include all forms of equipment, from domestic appliances to vehicles and major industrial installations. Further, the supply of professional and trade services implies a prior investment in training, which also creates a durable asset.

Each of these durable assets has a limited useful lifespan, and hence a proportion of total economic activity each year must be used for durable asset acquisition, to maintain the stock. In a stable population, the annual investment would be inversely proportional to the lifespan of the asset class: 100 divided by the lifespan in years equals the annual percentage turnover. Thus, if power stations last for 50 years, on average 2% of them would need to be replaced each year to maintain a stable stock. If municipal buses are in service for 10 years, 10 per cent of the fleet would need to be purchased per year.

It is important to recognise that the total value of all durable man-made assets is several times greater than total annual GDP. In any one year, a society can only afford to provide a fraction of the stock. Durability allows many years' worth of acquired assets to be enjoyed at any one time. Quality of life therefore depends greatly on the durability of the things we create.

Population growth requires that the stock of all durable assets is expanded at the same growth rate, in order to maintain the current level of productivity, amenity and service provision that the population has already attained.

The cost of population growth is disproportionately higher than the rate of growth itself. For instance, a cost-weighted average lifespan of all infrastructure is in the order of 50 years, implying a replacement need of 2% of the total stock per annum. A population growth rate of one per cent per year implies the need to expand the stock by 1% in that year, in order to keep pace with population growth. Consequently, society's burden of annual infrastructure acquisition is raised from two per cent to three per cent of the existing stock, a 50 per cent increase.

Similar calculations can be made for other categories of assets. Illustrative examples are given in Table 1. If trained professionals on average spend 33 years in the workforce after graduation, a stable population would need to graduate 3% of the workforce in that profession annually to replace retirees. If that population suddenly started to grow at 1% per annum, it would need to graduate 4% of the workforce: 3% to replace retirees plus 1% to expand the workforce. This is a 33% increase over the burden carried by a stable population. The result is that the percentage increase in annual acquisition needed for each 1% growth is equal to the working lifespan in years.

Table 1. Illustrative examples of the burden of expansion to cater for a population growing at 1% per annum, relative to that of maintaining a constant stock to serve a stable population.

Asset class	Working lifespan	Annual acquisition burden to maintain a constant stock	Annual acquisition for maintenance and expansion by 1%	Increase in burden per 1% population growth
Power stations	50 years	2%	3%	50%
Buses	10 years	10%	11%	10%
Nurses	33 years	3%	4%	33%

In proof-of-concept analyses based on Australian and UK data (O'Sullivan 2012, O'Sullivan 2013a), national accounts of Gross Fixed Capital Formation (GFCF), Household Final Consumption Expenditure, and tertiary education were used to collate national spending on asset classes of different estimated lifespan. Historical population data allowed the estimation of the proportion of stock in each lifespan group needing to be replaced in any year (accommodating the effect of growth over the lifespan of an asset class reducing the turnover rate by diluting the oldest cohort due for replacement). Population growth rate in any year dictated the proportion of current stock needing to be acquired for capacity expansion. Thus the actual spending on durable assets could be apportioned to maintenance and expansion.

Using this methodology, it was found that the replacement value of capital stock in the UK averaged 6.9 times GDP over the period 1968 to 2007 (O'Sullivan 2013a), and 6.5 times GDP between 1964 and 2004 in Australia (O'Sullivan 2014a). Thus, over that period, capital widening cost 6.9% of GDP per 1% population growth rate in the UK, and 6.5% of GDP per 1% population growth rate in Australia. While the UK averaged only 0.25% per annum population growth, the burden of capital widening was only 1.76% of GDP, but it has since climbed to nearer 5% with elevated population growth. For Australia, growing at an average of 1.44% per annum, the burden was 9.3% of GDP over the 40-year reference period.

The latter study found evidence for an escalation in cost per added person after population growth rate accelerated since 2004, suggesting that diseconomies of density and growth rate outweigh economies of scale. Diseconomies of density include requiring more costly structures to cope with congestion, such as road tunnels and high-rise buildings, or substituting environmental services (such as gravity-fed water supply) with technological alternatives (such as regionally pumped water or desalination). Diseconomies of growth rate include shortening the lifespan of facilities through the need to replace them with higher-volume versions, or to reallocate scarce space to higher priority uses.

It should be stressed here that 'capital widening' is a recurrent cost of a growing population (Figure 1). It is required merely to stand still, in terms of economic and social standards. It is

common for all spending on infrastructure and equipment to be regarded as 'investment', justifying financing through debt. But there is no future time when such investment pays off. Debt financing, or private investment requiring additional fees for access to infrastructure which was previously free, merely adds the cost of servicing this 'investment' to the cost of further capacity expansion in subsequent years. Thus, failure to pay for expansion with current income decreases future ability to keep pace with growth, either by adding debt repayments incurred to expand infrastructure, or by crowding the infrastructure which was not sufficiently expanded. Although Sauvy (1958) termed this asset acquisition burden 'demographic investment', here it is argued that it is more appropriately viewed as a direct burden of growth rate, the alleviation of which provides an 'infrastructure dividend' of population growth reduction.

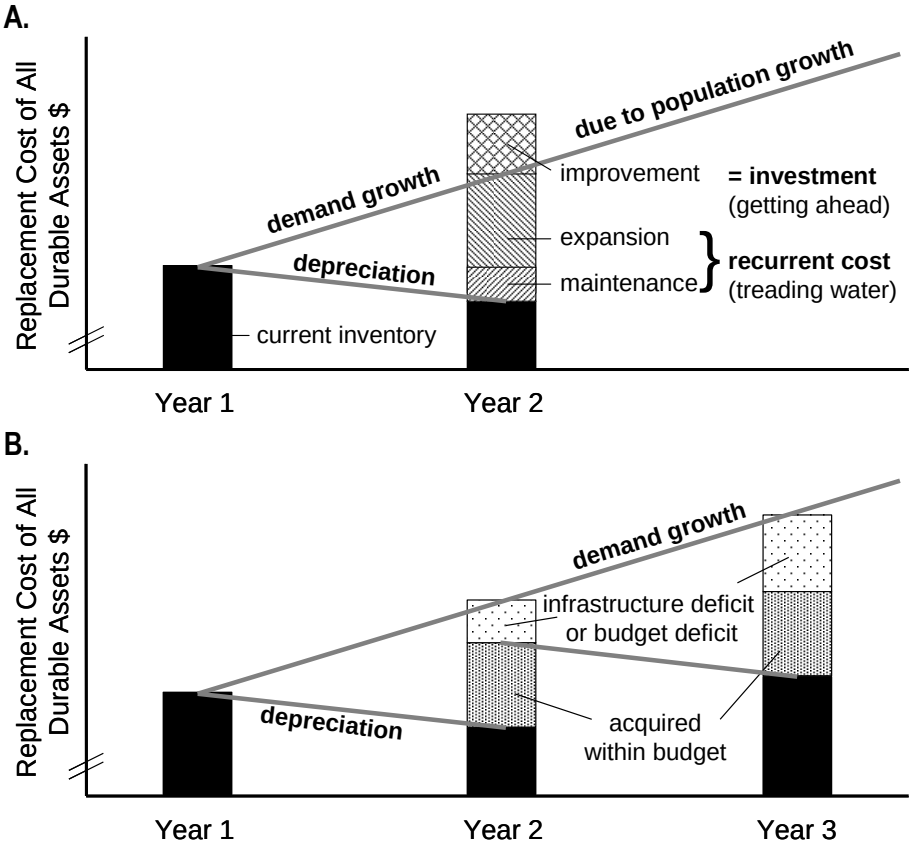

Figure 1. Conceptual illustration of: A. the components of durable asset acquisition as recurrent cost or investment, and B. the escalation of deficit if capacity expansion fails to keep pace with population growth.

The application of 'infrastructure dividend' in Africa

It would be useful for African policy-makers to know how much it costs to equip an extra citizen with the infrastructure and service capacity to be no poorer than current citizens. At the national scale, what proportion of GDP is being diverted to this purpose? How much economic capacity would be freed up by a reduction in population growth rate of 0.1%? In whose hands would this extra spending power lie, and how could it be spent?

There are a number of differences between the economies of these nations and those of developed countries. In addition, there are greater limitations to the data through which we

can quantify them. This section does not attempt to resolve these issues, but only to explore the feasibility of pursuing this line of inquiry.

When population growth is changed through a change in birth rate rather than a change in net migration, there are differences in timing of specific impacts. The latter immediately impacts household formation and employment opportunities. The former may immediately impact women's engagement in the workforce (a demographic dividend) and demand for health services, and will soon affect education systems, but the need to expand the provision of housing and jobs will not be diminished for a couple of decades. However, in both scenarios, an increase in household saving capacity is expected, either through reduced expenditure on children or a reduced proportion of underemployed people and of highly-indebted new mortgagees among households.

There are also differences in what is being measured, and how capital widening is borne by the community. Most African countries still have large subsistence sectors, in which not only food but materials for construction and equipment are derived from the natural environment directly. They also have significant informal sectors, where monetary or in-kind trade occurs without being measured. Official GDP statistics may estimate the scale of such activities differently from one country to another (Jerven 2013). Where economic data are of variable coverage, it may be useful simply to examine the proportion of imports dedicated to capital widening, and their impact on balance of trade.

Although a majority of people may be currently employed in the subsistence and informal economy, capital widening may be mostly required through the formal economy. Increasingly, additional people are moving to cities, and even those in rural settings are opting for a higher proportion of purchased materials for construction, exchanging traditional tools for manufactured equipment and accessing the services of professional personnel. If GDP represents the economy of the urban and industrial areas, rather than the nation as a whole, then it may be that the relevant population growth rate is that of the urban and industrial areas also – often double that of the nation as a whole.

Let us take an example, in which the total stock of infrastructure and equipment in a city has a replacement value of seven times the GDP generated in that city annually. While the national population growth rate may be 2.5% per annum, that of the city is 5% per annum. This implies that 5 x 7 = 30% of total economic activity must be directed to building or acquiring new infrastructure and equipment, merely to prevent the population getting poorer. The rural areas, with higher birth rates but high out-migration, may not be growing as fast. But the government's capacity to deliver services to them will be constrained by the demands of capital widening in the city.

This dynamic may go part of the way to explaining the apparent inequity of resource distribution, where rural regions appear relatively neglected. Despite being poorer, they may attract a smaller fraction of government spending. It may be the growth rate, rather than the development deficit, which is dominating the allocation of resources. Only a reduction in growth rate allows increased attention to development deficit.

Contribution of the infrastructure dividend to overall impacts of population growth

Population growth acts on economic dynamics through several dimensions, including density, age structure, and growth rate.

Density (the ratio of people to the natural resource base) is most often discussed in terms of regional carrying capacity, and is manifested through food and water insecurity, or environmental pollution and degradation. While neo-liberal economics tend to disregard natural resources as a limiting factor, relying on any form of income generation to provide access to all necessary resources through global markets, this strategy exposes the population to increasing risk of external shocks, and forces activity to be export-oriented in an increasingly competitive market. The niches for dense, trade-dependent countries are already crowded.

Age structure has already been discussed in terms of the 'demographic dividend'. However, in countries where adult labour is oversupplied and underutilised through lack of physical and human capital, the benefits of a large working age proportion may be weak. The much-discussed problem foreseen for 'ageing' societies, which are experiencing a declining proportion of working-age people, has not yet resulted in any shrinkage of workforce. So far, ageing countries have maintained similar proportions of people in the workforce through greater workforce participation rates (O'Sullivan 2014b, Betts 2014). The responsiveness of participation rates to labour demand suggests that labour is oversupplied even in ageing countries. Having fewer people chasing the available jobs has more advantages than disadvantages.

Growth rate, as a factor with unique impacts, has been relatively neglected in the population-development discourse. The infrastructure dividend is a function of growth rate, but it is not the only one. Dilution of capital per worker, as Solow (1956) observed, is a drag on productivity. It is also widely accepted that oversupply of labour puts downward pressure on wages and shifts the distribution of the gains of economic activity from labour to capital. In this way, growth rate drives widening inequality of income. Furthermore, the inflation of land values is driven by population growth rate. While competition for land may be seen to be related to population density, it is the expected ongoing increase in demand which attracts speculative investment of capital. The wealth-circulating powers of a market economy are truncated as an ever-greater proportion of wage income is diverted to economic rents. The constraint on consumption demand is compensated by expanding debt levels, mortgaged against inflated land values. Thus population growth rate drives widening inequality and deepening debt. An increasing proportion of the population live under conditions tantamount to debt bondage. These dynamics tend to prevail wherever population growth has not been matched by expanding access to natural resources (land and energy).

The usual focus of macro-economics on aggregate GDP and GDP per capita neglects inequality and debt. The demographic dividend has been used to explain part of the impact of fertility reduction on GDP per capita, by reasoning that a growth in working-age proportion of the population may take the credit for the same percentage of growth in GDP per capita. This explanation is questionable where labour is clearly oversupplied. It is generally stressed that the demographic dividend is an opportunity which must be capitalised, through education and employment opportunities, before it can yield benefits. What has not been made clear is that the low 'capitalisation' of labour before the fertility transition is primarily due to the burden of capital widening. It is the infrastructure dividend which enables labour to be better capitalised as fertility falls. Hence much of the benefit attributed to the demographic dividend may be more accurately attributed to the infrastructure dividend.

One way to conceptualise the burden of 'capital widening' in relation to demographic dependence, is to see this burden as attributable to a sub-set of dependent people, the 'not-yet-added'. The not-yet-added pay no taxes and do no work, so the costs of providing for them are born by the current workforce. Figure 2 illustrates the impact on dependency ratio, when this burden of population growth rate is included. Dependency ratios assume that the wealth generated by working age people must be distributed to the whole population, so the larger the proportion of working age, the easier it is to provide well for everyone. When capacity expansion for the not-yet-added is included, the challenge for rapidly growing countries is dramatically increased, while the disbenefit of an ageing population is largely annulled.

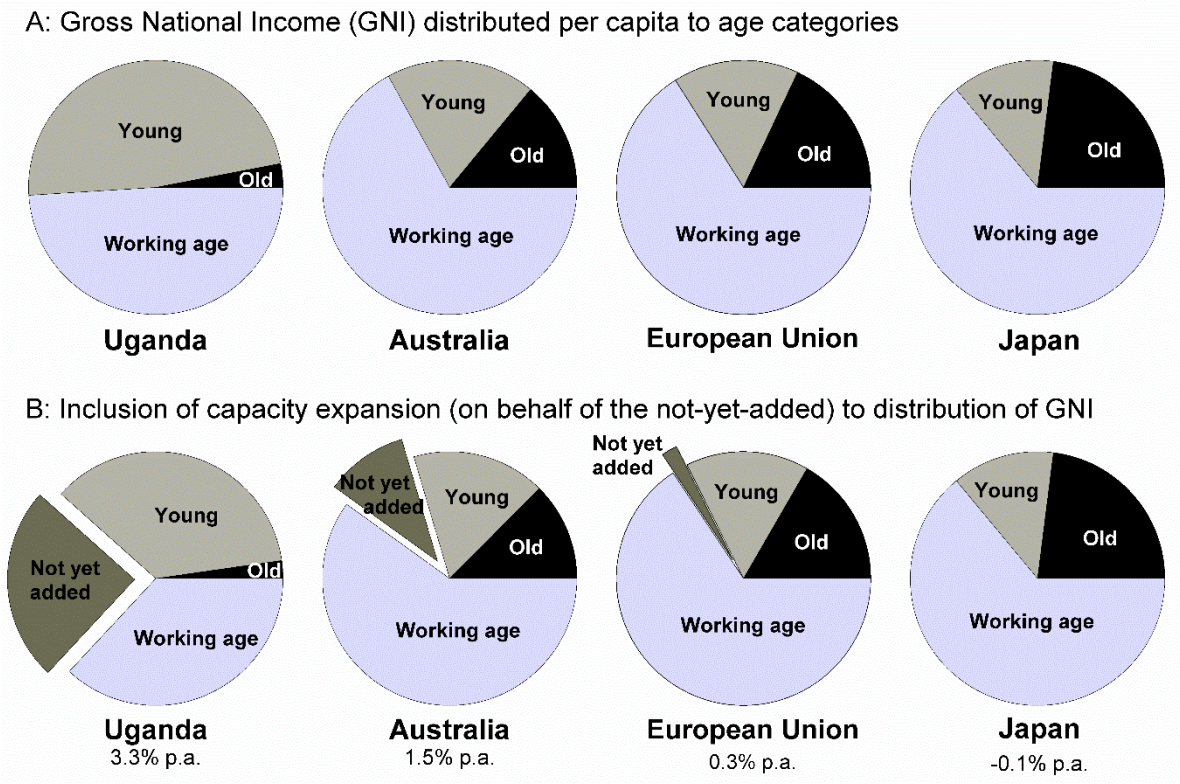

Figure 2. Economic dependency ratios, A: the pie of gross national income divided among demographic categories, on a notional 'per capita' basis (i.e. according to the percentage of population under 15, 15-65 and over 65), and B: the distribution of GNI when the cost of capacity expansion is included. Capacity expansion (the cost attributed to the 'not yet added') is provisionally assumed to have a cost of 6.7% of GNI per percentage of annual population growth rate. Current population growth rates and percentage under 15 and over 65 are from Population Reference Bureau (2011).

Evidence for the macroeconomic impact of high fertility

An analysis of country level data found that fertility decline was not dependent on levels of wealth or education, but was very responsive to policies and programs intended to reduce fertility (Supplementary Information; O'Sullivan 2013b). Conversely, economic advance was found to gather pace only after fertility had fallen below three children per woman. The relationship between TFR and GDP per capita showed a similar, steeply concave curve for most countries, regardless of their rate of fertility decline. Indeed, rapid transition and slow transition countries followed the same path, indicating that fertility decline has been almost

universally a pre-requisite for economic advance. The pace of economic advance has depended on the pace and extent of fertility decline.

On the basis of a few studies in which family planning interventions could be analysed as a quasi-controlled experiment (most notably the cases of Matlab in Bangladesh and Navrongo in Ghana), it is often claimed that family planning causes a quantum of fertility decline, of 1 – 1.5 units (Canning et al. 2015). The diverse population programs and fertility transitions among the community of nations offers an alternative, more robust experiment. Here it is evident that family planning interventions act on the rate rather than the quantum of fertility decline. The quantum thus depends on how long the program initiatives persist (Supplementary Information, Figure S1). Family planning programs have driven rapid decline to below replacement rate in countries such as South Korea, Thailand and Iran. However, where programs were neglected before replacement was achieved, such as in Indonesia, Bangladesh and Algeria, fertility has stalled or rebounded. To reap the economic advantages of population stabilisation, the importance of maintaining programs to well below replacement rate should be stressed.

Some economic modelling exercises give a deceptive impression that the benefits from population growth reduction are modest. Ashraf et al. (2013) compare modelled outcomes for Nigeria under the UN's medium and low fertility projections (UNDESA 2011). These two projections have fertility falling in parallel, only 0.5 units apart. This is an improbably trivial impact of population policies. Figures S1, S2 and S5 show that the more common experience has been a sustained divergence of TFR based on differing rates of fertility decline. Ashraf et al. (2013) further present the impact of lower fertility as a variation from the baseline 'medium fertility' scenario. This fails to consider that the baseline scenario may have no per capita economic growth, or even negative growth. The data presented in Figure S3 show that this has been the rule, rather than the exception, for all countries as long as fertility remains above four, and development only gathers pace as fertility declines from three to two children per woman. The infrastructure dividend explains these dynamics, in a way that previous models have failed to do.

The message of the demographic dividend is that reducing fertility may offer a window of improved economic performance, if certain conditions are met. The impression given is that this benefit is optional, conditional and ephemeral. The message of the infrastructure dividend is that lowering fertility is an absolute prerequisite for economic advance. To delay fertility decline is to delay development.

Conclusion

This analysis builds the case for population growth reduction to be reinstated as a development priority. Even before pinning down a precise figure for the burden of capacity expansion in a sub-Saharan African context, this perspective on the burden of population growth clarifies previously equivocal positions in the literature. The theses of Boserup (1965) and Simon (1981), who hypothesised that population growth will drive enrichment through innovation and efficiency gains, have not been supported by the evidence of the subsequent decades. The consistent economic success of those countries which chose to reduce population growth actively, in contrast with the consistent failure of those where fertility remains high, can no longer be dismissed as circumstantial. The infrastructure dividend provides an important factor in explaining their success.

Supplementary Information:

Evidence for population growth hindering development

The literature examining the relationship between population growth and economic development is vast, and it is not intended to review it here. This section presents an exploration of the timing and rates of change of TFR and GDP per capita using country-level data.

A. Fertility decline associated with national population-focused family planning programs

Countries known to have implemented strong family planning programs showed rapid decline in TFR immediately after program start. Some of these time courses are shown in Figure S1. The start dates varied widely, evidently determined by domestic policy change rather than global or regional factors. Over the first two decades following program initiation, rates of fertility decline were typically between 1.5 and 3 units per decade. These rates contrast with the slow decline, and recent stalling of decline, in less developed and least developed countries in aggregate.

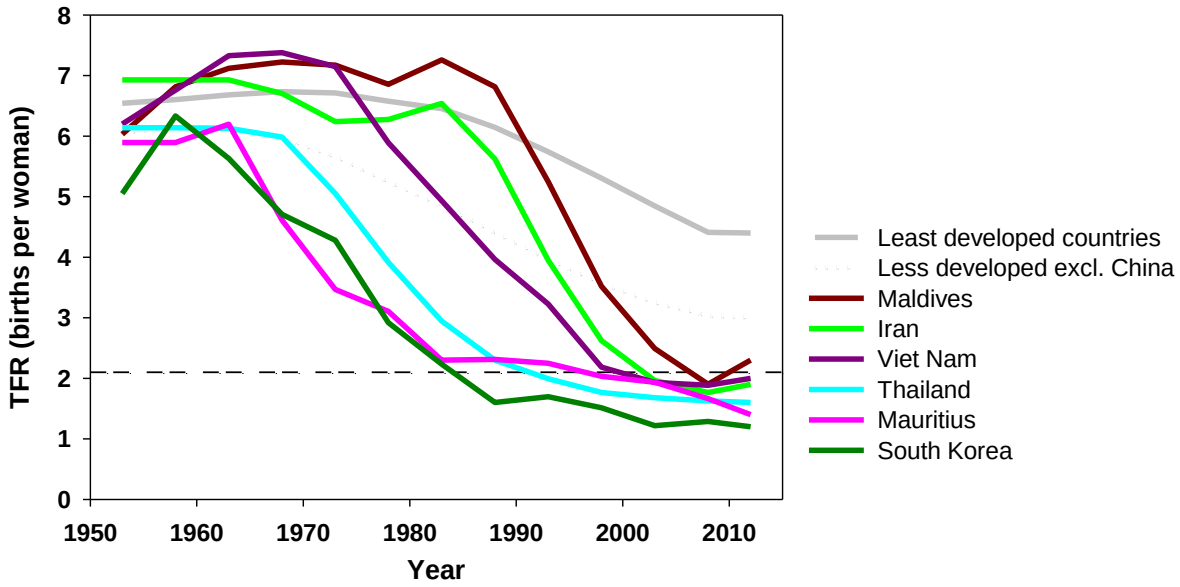

Figure S1. Time course of total fertility rate (TFR, births per woman over her lifetime) for selected countries which implemented population-focused voluntary family planning programs at differing times, showing rapid change in fertility, compared with aggregate TFR for less developed and least developed nations. Data from UNDESA (2011) and Population Reference Bureau (2013).

B. Comparison of family planning countries with regional neighbours

To explore the relationship between TFR and GDP per capita time courses, selected countries which implemented voluntary measures to reduce fertility (population-focused family planning) were compared with neighbours in the same region which did not (O'Sullivan 2013b). Five such pairs each followed the same pattern (Figure S2): rapid divergence in total fertility rate (TFR) between the country with proactive population policies and that without, preceding a divergence in wealth. Subsequently, GDP per capita diverged strongly, with growth typically accelerating after TFR fell below three. The relationship between TFR and GDP per capita was usually strongly concave, as fertility decline preceded wealth

acceleration. This contradicts the commonly held belief that enrichment is a dominant driver of fertility decline. Indeed, the close alignment between the paths taken by family planning and non-family planning countries suggests that fertility decline was a pre-requisite for development.

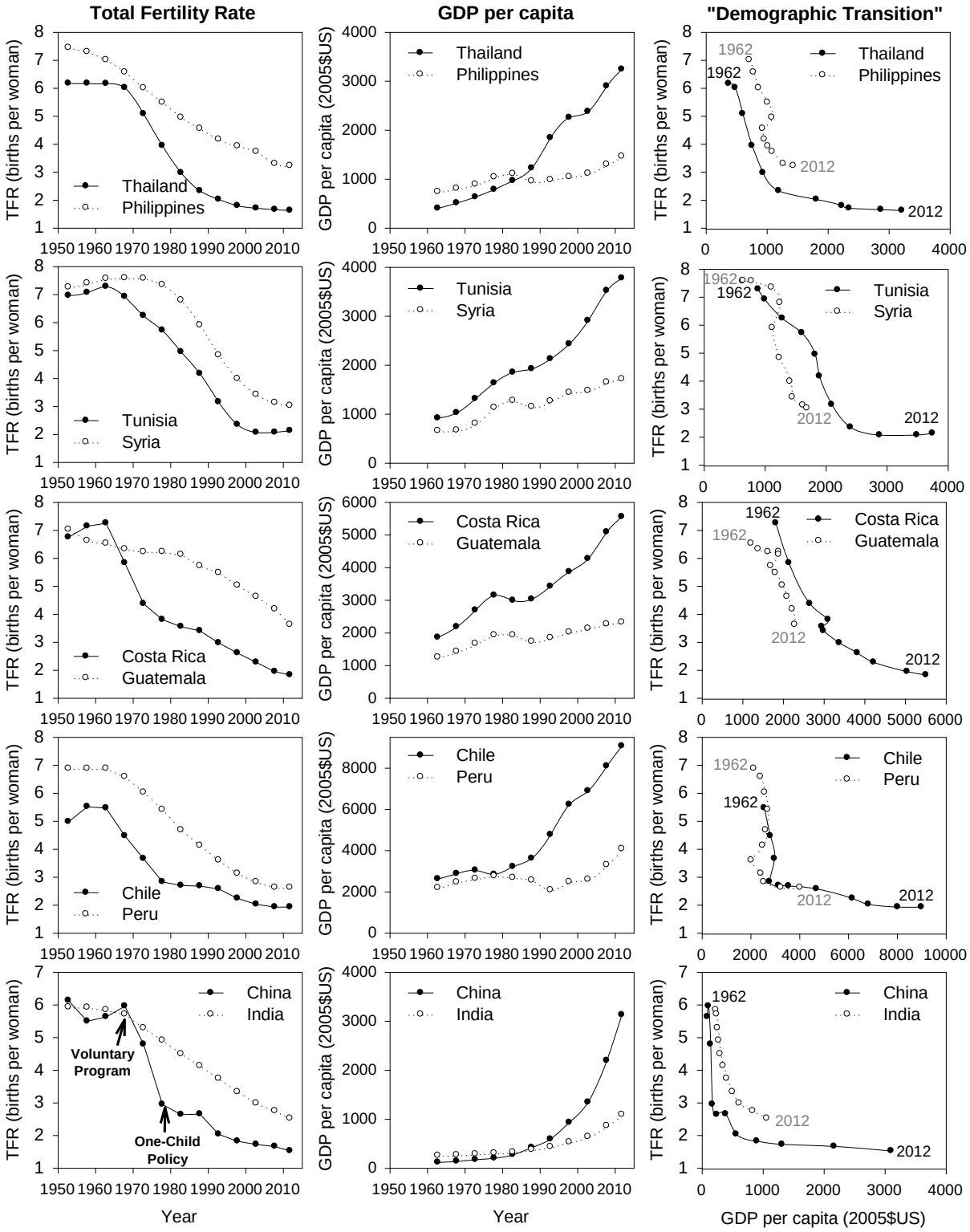

Figure S2. Fertility and wealth time courses for five nations which adopted family planning (solid lines) in contrast with comparable countries in the same region (dotted lines) which were weaker or later adopters of family planning. Left: the change in total fertility rate (TFR,

the average number of children born to each woman over her lifetime) over the period 1950 to 2012; middle: the average GDP per capita over 5-year intervals from 1960 to 2015 (adjusted to constant year 2005 US$; and right: the relationship between TFR and GDP per capita.

C. Direction of causation between fertility and wealth change

To investigate the direction of any causal effect more closely, all nations with available data were used to plot the change in TFR over a 5-year interval, as a function of the level of GDP at the start of the interval, and the change in GDP per capita as a function of the TFR at the start of the interval. Each country provided multiple data points, one for each interval for which both TFR and GDP data were available.

This analysis is shown in Figure S3. Scatter plot A shows no relationship between wealth and rate of fertility decline. In contrast plot D shows that significant economic advance has been rare when TFR exceeds 3, and much more probable and greater in magnitude as TFR declines to below 2. Dot colour in the scatter plots shows the date in the middle of the period represented by the datum. The colour distribution indicates that there has been little temporal shift in the relationship of fertility change to wealth, but that the likelihood of rapid economic betterment in high fertility countries has diminished since the 1970s.

These distributions are summarised in the box plots. In plot B, the smaller fertility change at the highest wealth levels is most likely due to them already having low fertility rates. Plot C shows that, when those with initial TFR below 2.0 are removed from the analysis, the range of fertility decline is similar at all levels of wealth.

In plot E, it is clear that rapid economic growth has been far more common in low fertility countries. Low fertility did not guarantee economic advance, but these data suggest that it enabled it, or conversely, that high fertility prevented advance.

Given that short-term economic change can be erratic, the pattern of change over the subsequent 20 years was also examined (plot F). Here, the consistent influence of low fertility on economic advance is more clearly evident. Almost none of the low fertility countries went backwards economically over two decades, and the very low fertility group outperformed all others. It should be remembered that the TFR is that which applied at the start of the period, and it may have declined considerably during the 20 year period. Thus some instances of modest economic advance in countries with initial TFR between three and five may be associated with subsequent fertility fall.

It is also evident that very low fertility has not produced negative economic outcomes up to 2010. This sample includes countries which had maintained low fertility for decades prior to the period measured, and some which experienced population decline during the period measured. The widely theorised drag of population ageing on economic performance is not supported by these data. This supports the conclusion of Betts (2014) and O'Sullivan (2014b) that ageing has not to date reduced the workforce (employment per capita) of countries as workforce participation naturally increases in response to demand for labour.

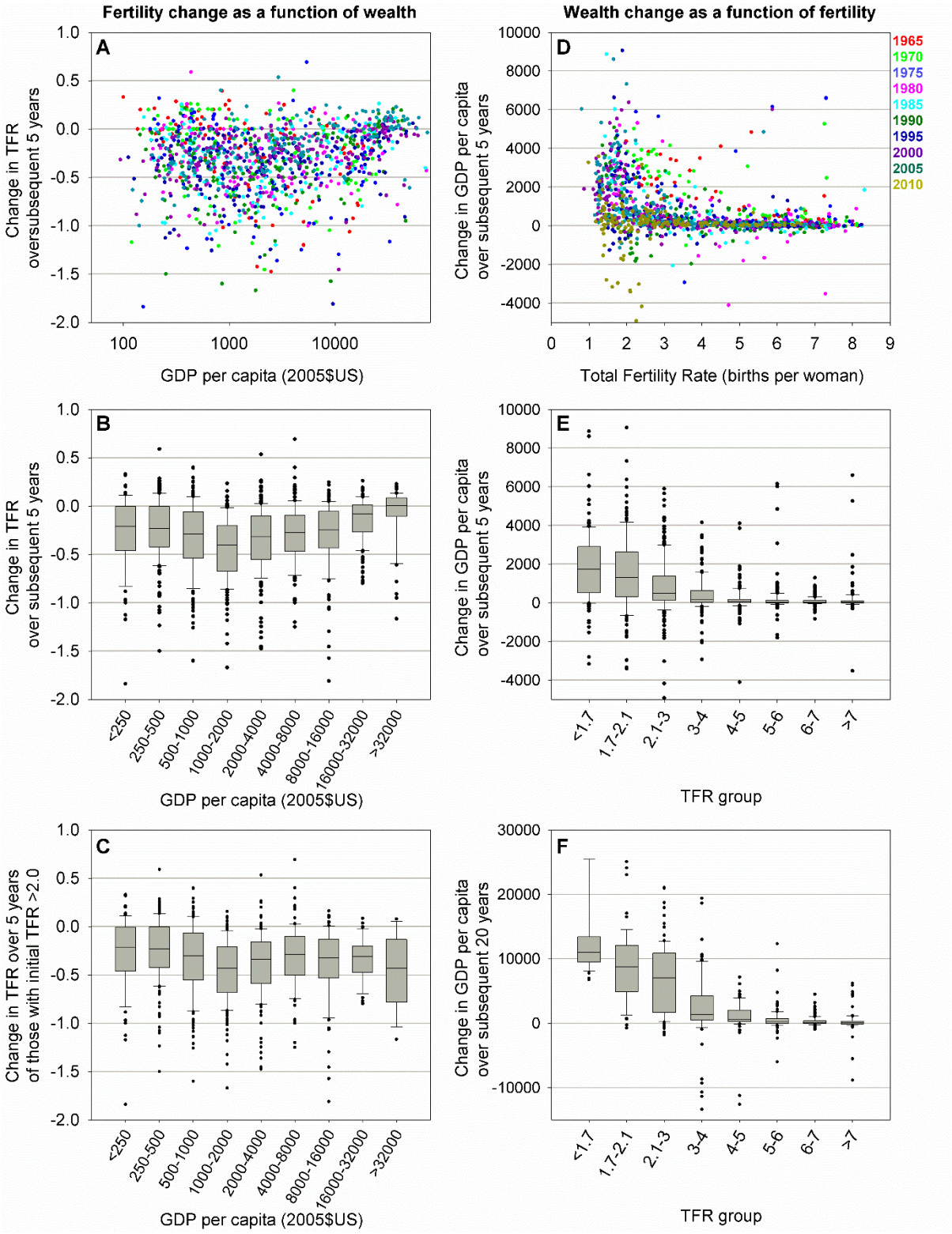

Figure S3. The relationship between the rate of fertility decline and level of GDP per capita (charts A – C) and between the rate of change in GDP per capita and total fertility rate (charts D – F). Data are for 5-year intervals between 1960 and 2010, for all countries with relevant data. Most countries have multiple data entries, one for each 5-year period. Box plots show the data median, the 25th to 75th percentile within the box and whiskers span to 10th and 90th percentile, with outliers individually plotted.

D. Direction of causation between fertility and girls' education

A similar analysis examined the relationship between girls' education and fertility decline (Figure 4). "Primary completion rate, female (% of relevant age group)" (World Bank indicator code SE.PRM.CMPT.FE.ZS) was chosen as the metric with greatest coverage in the World Bank dataset. (While secondary education may be a more relevant metric, insufficient data were available.) Data start from 1970 and are much less comprehensive than for GDP per capita. Available data were averaged across five year periods, without adjustment for missing values, to match the 5-year TFR data. In order to maximise the number of intervals available for plotting, breaks in time series were interpolated assuming linear change between the previous and next available data.

The charts in Figure S4 show that, while very low levels of girls' educational attainment were more commonly associated with slower fertility decline, levels as low as 30% primary completion posed no barrier to rapid fertility decline. Similarly, while the most rapid advances in educational access are associated with middle fertility levels, neither high nor low fertility has much influenced the range of outcomes possible. These data suggest that both fertility decline and girls' education have been covariate with other trends, likely to be related to the level of focus on women in development, but have not had strong influence on each other at the country level.

This does not contradict the widely reported difference in fertility between more and less educated women within countries. It merely suggests that girls' education is neither necessary nor sufficient to drive fertility decline. This concurs with the conclusions from time series presented by O'Sullivan (2013b).

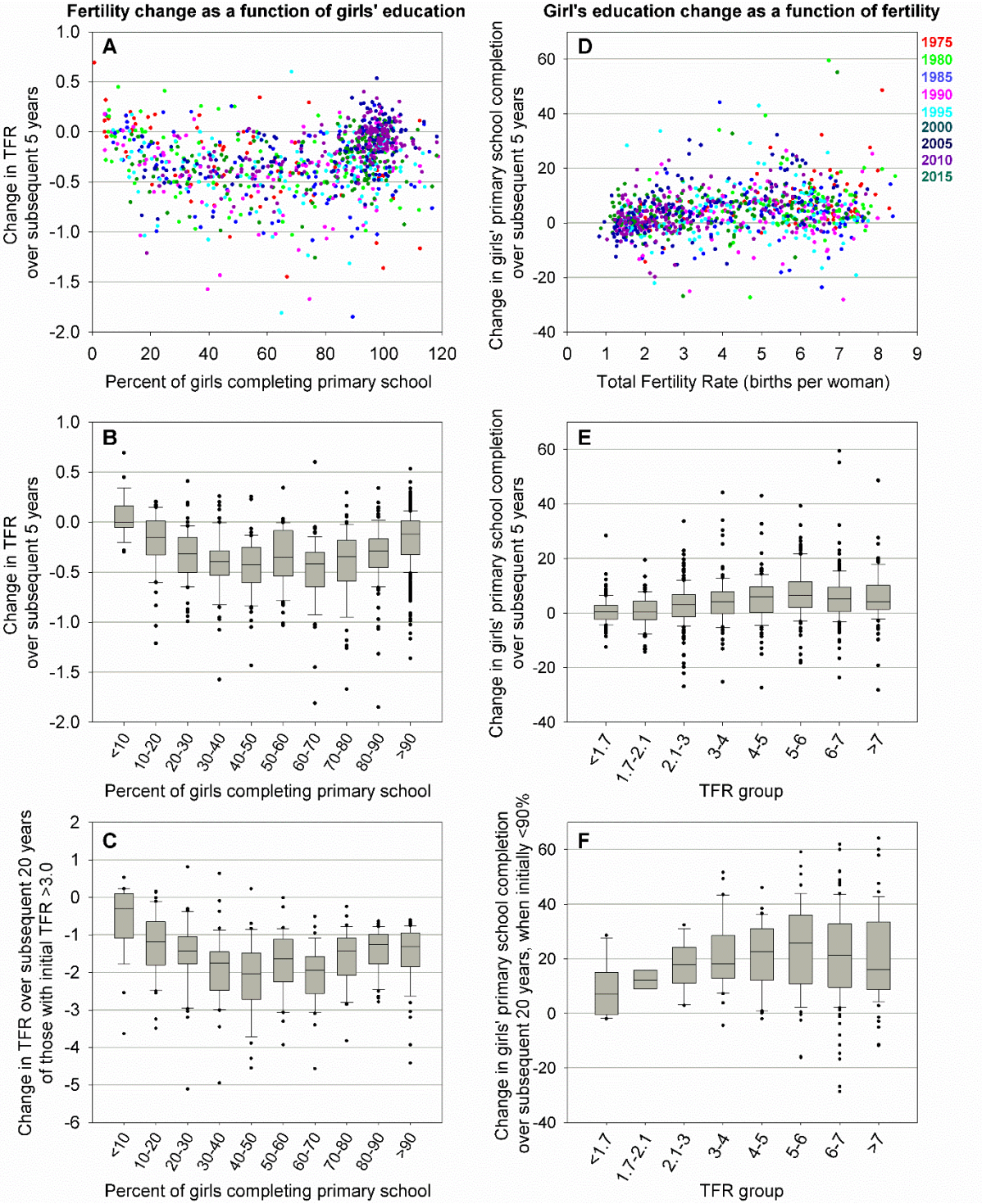

Figure S4. The relationship between the rate of fertility decline and percentage of girls who have completed primary school (charts A – C) and between the rate of change in girls' primary completion rate and total fertility rate (charts D – F). Data are for 5-year intervals between 1970 and 2010, for all countries with relevant data.

E. Average experience of rapid, medium and slow transition countries

To further investigate the patterns observed in paired country comparisons, countries were assigned to a group based on their maximum change in TFR across 20 years. Group 1

contained countries where TFR fell after a particular date, at a rate exceeding 1.5 units per decade, to near or below replacement (unless insufficient time had elapsed since the start of decline). Most of these countries are known to have adopted family planning policies and programs around the time that the birth rate began to fall. Group 2 also showed considerable decline in TFR after a given date, but at a slower rate, between 0.8 and 1.5 units per decade. Group 3 showed no distinct start date for fertility decline, and still have fertility rates above 3. Group 4 had fertility rates below 5 and falling at the start of the UN data series in 1950-55, so it was not possible to designate a start date. Most Group 4 countries can now be considered 'post-transition' countries, with fertility rates below replacement level.

The contribution of migration to population change was also recorded for each five-year period, and an average per cent contribution of migration was calculated over the period from 1970 to 2010. This figure was used to sort nations within each group. Those with an average migration contribution outside the range 15% to -15% were excluded from aggregate group data. This was to ensure that the change in population was as far as possible a reflection of the change in fertility.

The sixteen countries included in Group 1 were Algeria, Bangladesh, Bhutan, Cambodia, Chile, China, Costa Rica, Iran, South Korea, Libya, Maldives, Mongolia, Oman, Thailand, Tunisia, Viet Nam. Group 1 countries rejected due to high migration were Hong Kong, Macao, Singapore, Aruba, Kuwait and Saudi Arabia (high immigration), and Mauritius and Guyana (high emigration). Note that China is included despite the presence of coercive programs from 1979, because most of the fertility decline occurred under the voluntary family planning program in place from 1970 to 1978. (Note also that the data are not population-weighted, so China's statistics have no more weight than those of Bhutan or Maldives.)

For each country in Group 1 and Group 2, a start date was assigned, approximating the year in which family planning programs were widely introduced. The data on TFR provided by the UN only gives estimated averages across five-year periods, so these dates were only estimated, with the help of historical accounts of program initiation where available. The natural increase in population and change in per capita GDP were then calculated relative to the start date for subsequent five-year intervals. In this way, members of each group were synchronised with respect to their population program. Once synchronised, averages across the group were then taken. The same calculations were performed for Group 3 and 4, using a uniform start date of 1970.

The average data for Groups 1, 2 and 3 are given in Figure S5. Group 1 achieved replacement level fertility (around 2.1 children per woman) in about one generation (Plot A). Its population course (Plot B) shows a declining slope, meaning that each year the population increases by a smaller amount than the year before. Typical Group 1 countries will peak with little more than twice their population when rapid fertility decline was initiated. While Group 2 countries have avoided some population growth, the slope of the population curve has continued to increase. This means they are still adding more people per year than when they started: the reduction in births per woman was insufficient to compensate for the combined effects of increasing number of women and continuing declines in mortality. Until the annual increment is falling, there is no peak population in sight, other than the prospect of population being capped by famine or war. Group 3 countries have, on average, tripled their populations over the same period. Many of them have increased population by a factor of five or more over the full 60 years of the UN data. They face a further doubling as a minimum from

whatever time they choose to address population vigorously, unless their overpopulation in the meantime causes a catastrophic rise in mortality.

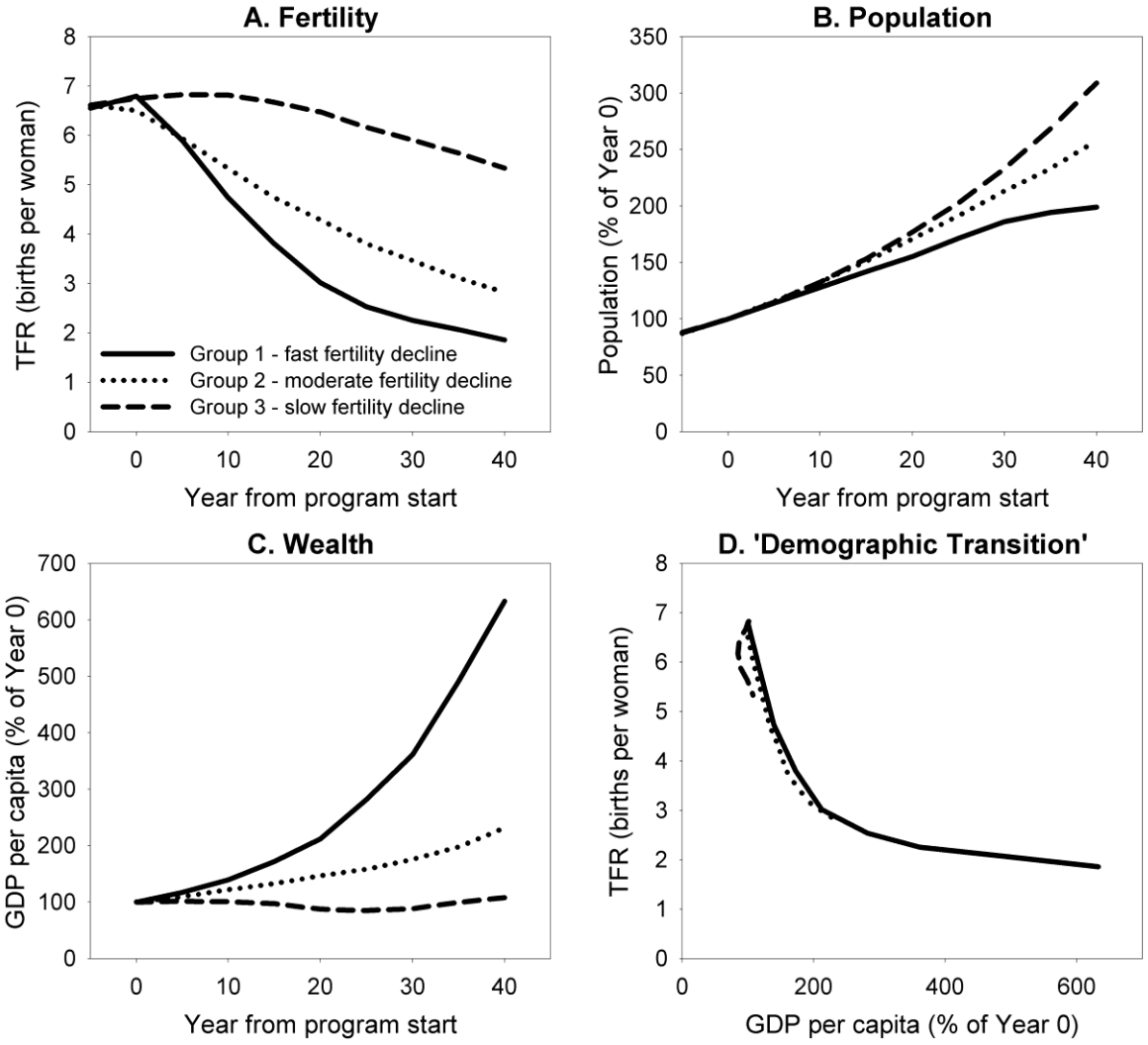

Figure S5. The time course of fertility, population and GDP per capita, and the relationship between TFR and GDP per capita, is compared for three groups of developing countries separated by their maximum rate of decline in TFR over two decades: Group 1: greater than 1.5 units per decade, Group 2: 0.8 – 1.5; Group 3: less than 0.8 units per decade. Year 0 is the approximate year of population program adoption, or 1970 for weak adopters. High migration countries excluded.

Even more striking than the population course is the time course for per capita wealth (Plot C). On average, the weak family planning adopters have not been enriched, regardless of other aid efforts. The rapid fertility decline countries have achieved rapid economic development, increasing in pace as the rate of fertility declined.

The relationship between TFR and GDP per capita (Plot D) not only shows steeply concave curves, as found for individual country case studies, but all three groups followed a similar path to date. If fertility had little bearing on economic outcomes, no criterion should have separated these lines more clearly than the one on which they are currently grouped. Yet we

see alignment, not separation. This provides strong evidence that high fertility and rapid population growth are severe impediments to development.

The change in GDP per capita shown on these plots is relative to the wealth at the start of programs, so it doesn't depict initial differences in wealth. At year zero, Group 1 was approximately 20% poorer, on average, than Group 2, but twice as rich as Group 3. Therefore, there is a possibility that poverty presented a barrier to family planning achievement in Group 3 countries. However, both Group 1 and Group 2 contained several countries below the average wealth of Group 3 at the start of their programs. The wealthier Group 3 countries have shown no more propensity for economic development than the poorest. We conclude that the precondition of wealth is not a major determinant of the rate of fertility transition.

This analysis is clearly a superficial glance at the dynamics of developing country economies, which have diverse drivers of, and barriers to, economic advance. It is acknowledged that GDP per capita is at best a crude measure of material wealth, and is not necessarily comparable between countries. However, the expression of GDP per capita relative to a base year avoids this lack of comparability. No matter how crude the estimates of GDP may be in the countries with a large informal sector, they are compared only with figures from the same source at different times. The patterns are sufficiently strong and consistent that no inadequacy of metrics could explain them away.

In relation to possible covariates that could provide an alternative explanation for this result, Acemoglu and Robinson's (2012) thesis "Why Nations Fail" places central importance on the difference between 'extractive' and 'inclusive' political institutions. The former exert the privileges of elites at the expense of the populous, while the latter seek to ensure a level playing field for economic participation and gain. It is intuitively possible that the dominance of inclusive over extractive political institutions may be characteristic of nations which chose to implement strong family planning programs. Empowering women does, after all, level the playing field, challenging traditional power structures. However, Jerven (2015) argues that good institutions are more often the result of, rather than the cause of economic growth. Scoones (2012) argues that the critical impact of Acemoglu and Robinson's inclusivity is security over property and over the gains of economic activity. Here, a clear connection can be made with the impacts of population growth diminishing people's access to land and productive resources, and to secure work and fair distribution of its gains. We might usefully question the direction of causal influence between population growth and 'inclusive' institutions.

All caveats considered, there seems no other likely explanation for these results than that high fertility has been the dominant constraint on economic advancement, wherever it has persisted. Policy choice appears to be a far greater determinant of the rate of fertility transition than either wealth or girls' education. The happy conclusion is that the means to accelerate development are accessible to any high fertility nation which chooses to prioritise fertility reduction through voluntary family planning and the promotion of small family norms.

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