Finding and Explaining Fast and Slow Mortality Transitions: A Taxonomy of Preston using Latent Growth Curve Analysis

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Abstract

Objective: Preston curves map life expectancy against GDP per capita. We sought to produce a taxonomy of Preston curves using historical data from 123 countries.

Methods: Country-specific Preston curves were constructed using all available data since 1960. Latent growth curve analysis (LGCA) was used to test the association of certain variables with an accelerated conversion of economic growth into health.

Results: Total fertility rate (TFR), HIV prevalence, and increased percentage of oil as a percent of the economy are associated with slower mortality transitions given constant GDP per capita, while population size and increased numbers of physicians associate with faster mortality transitions. The Preston relationship also varies by region.

Discussion: The average Preston relationship hides considerable heterogeneity between countries. This work offers a way to identify over- and under-performers along the Preston curve, relative to other countries with similar levels of important mortality predictors, and target them for qualitative and quantitative analysis of factors related to performance. Positive deviants suggest proven avenues for countries to leverage economic progress for health improvements. This method also enables more nuanced cross-country comparisons which can be helpful in setting mortality reduction goals.

Introduction

The relationship between economic growth and improved population health is intuitive and well-documented. In 1975, Preston demonstrated the strong relationship between life expectancy at birth (LEB) and the logarithm of per capita GDP (logGDPpc) (1). This pattern holds across many countries, particularly those in Europe, which have all made the transition from widespread poverty and low life expectancy to healthy and wealthy populations. This "mortality transition" occurred before the advent of modern medical technologies such as antibiotics, vaccines, and contraceptives.

However, many non-Western countries do not follow the European Preston curve. The modern environment in which many developing countries are pursuing public health is very different from the early 20th century environment in which European countries achieved their mortality transition. The availability of new health technologies and practices should enable developing countries to surpass the pace of health improvement set by European countries.

The "Bangladeshi Miracle" (2) of rapid gains in life expectancy during a time of modest GDPpc growth provides but one example of a country that significantly outperforms the Preston curve. Similarly, countries with high HIV prevalence have suffered well-documented setbacks to life expectancy despite some undergoing rapid economic growth (3). Many other countries do not fall on the average curve but substantially above or below it (4).

Many global policies and pronouncements do not take into account this considerable heterogeneity between countries. For example, Millennium Development Goals 4 and 5 call for a two-thirds reduction in child mortality and a three-fourths reduction in maternal mortality, respectively, for all countries between 1990 and 2015 (5). These goals emerged out of agreements and resolutions from world conferences organized by the United Nations in the first half of the 1990s (6), and cited the reduction by three-quarters of infant mortality in China, Sri Lanka, and Vietnam from 1960-1990.

However, it has been regularly documented that while some developing countries are on track to meet these targets, the majority are not (7) (8), with some having made only minimal progress.

It is likely that goals extrapolated from the aforementioned Asian successes may not have been appropriate for global application, given substantial differences between countries. This work aims to first identify different trajectories of Preston ascent. It then aims to identify factors that lead to a faster or slower mortality transition given constant levels of GDPpc. Finally, it provides a sophisticated method for the more nuanced setting of achievable and applicable mortality goals for all countries when MDGs 4 and 5 are up for renewal in 2015.

Methods

Data Selection

Various databases were examined for the most comprehensive time series data for GDPpc, LEB, and possible interacting variables (9) (10). Of these, the World Bank databank (11) provided the greatest number of indicators over the time period of interest. Data for 180 countries was available for LEB, under-5 mortality, GDPpc for at least 20 consecutive years. Of these, 57 were developed countries or former USSR territories and were excluded from the analysis. Of the remaining 123 countries, 59 provided full LEB and GDPpc data beginning in 1960; all countries provided data with occasional missing entries starting in 1990.

Qualitative Preston Curve Analysis

Preston curves were constructed for these 123 countries, using Gapminder as a data source and Sweden as a benchmark. Gapminder was used as a data source since it includes data beginning in 1800; Sweden was used as the benchmark since it completed its mortality transition before the advent of modern medical technologies. Different world regions were compiled onto the same graph to aid comparison.

Indicator Selection for Latent Growth Curve Analysis (LGCA)

Indicators were selected for analysis if they could be plausibly related to the relationship between LEB and GDPpc and were available for over 50% of all 123 countries since at least 1990. This criteria identified eleven candidate variables (discussed later) of significant interest, although this list was not meant to be exhaustive. Some, such as oil rents and HIV prevalence, were pursued after the qualitative Preston curve analysis.

LGCA

All analysis was completed using STATA 12 (12) using the xtmixed procedure.

Results

Qualitative Preston Curve Analysis

Several different patterns were indeed visible on qualitative inspection (Figure 1). Some countries, such as most of central America, appeared to track closely to Sweden's curve, while many in South Asia achieved gains considerably in LEB faster than Sweden did for the same GDP. Notably, oil-rich countries and those with high HIV prevalence significantly underperformed compared to Sweden's Preston curve. These apparent regional and country-characteristic differences suggested the need for quantitative analysis.

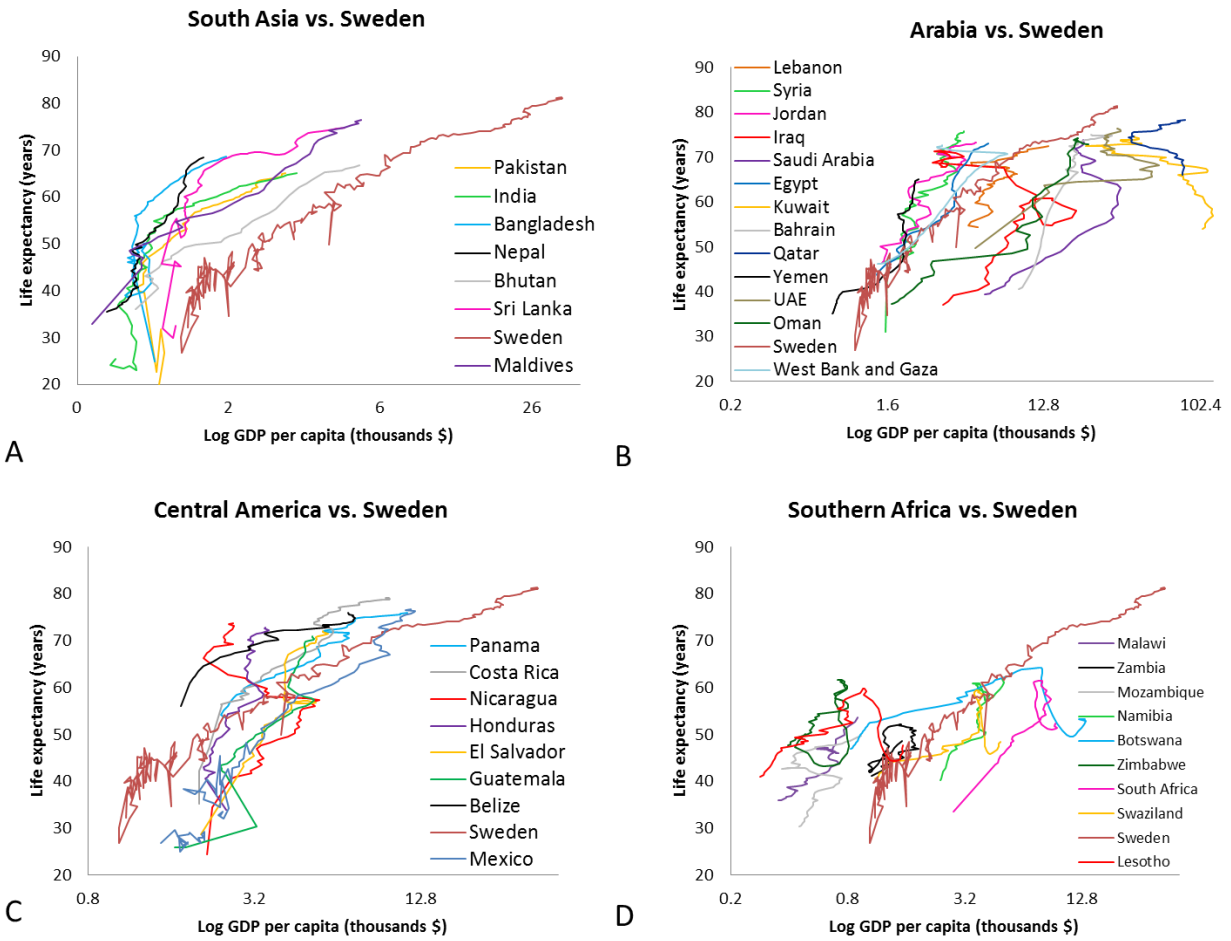

Figure 1. Qualitative Preston Curve Analysis. The Preston curve for each country in the given regions is compared to that of Sweden (dark red). A) South Asia. B) Arabia. C) Central America. D) Southern Africa.

Base Model Construction

Since LEB was more closely normally distributed than logLEB, and since the natural log of GDPpc (logGDPpc) was also approximately normally distributed (data not shown), LEB and logGDPpc were used for all data analyses. First LEB was plotted against logGDPpc (Figure 2). Because the relationship between LEB and logGDPpc was nonlinear, and remained non-linear when plotting logLEB against logGDPpc (data not shown), various polynomial models were considered. Points of significant leverage were noted at values of logGDPpc < 4.5 and logGDPpc > 10.6, the latter corresponding entirely to the United Arab Emirates. Removing these influential data points significantly improved the log-likelihood of the different models (Table 1), so these data points were

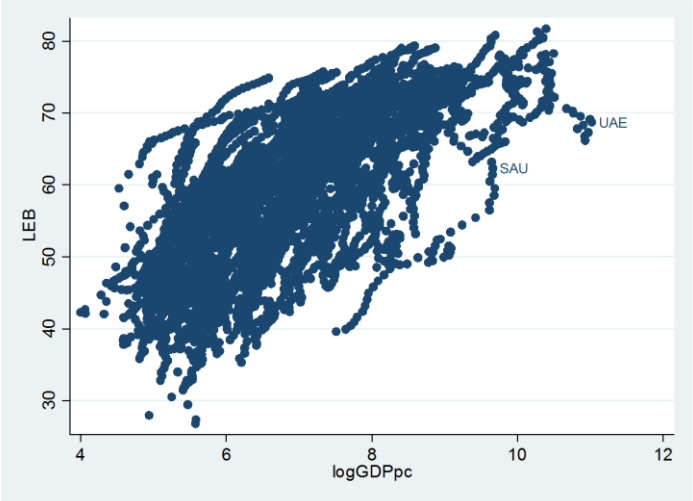

Figure 2. Scatter plot of LEB versus logGDPpc for all 123 eligible countries. SAU = Saudi Arabia; UAE = United Arab Emirates.

excluded. Saudi Arabia was also excluded using similar rational as that for UAE.

First a random intercept model was generated, allowing each country to have a different intercept. This is described by equation (1):

$$LEB_i = \beta_{0i} + \beta_1 * logGDPpc_i + \varepsilon_i \quad (1)$$

Our hypothesis was that the relationship between logGDPpc and LEB would vary by country. To test this, a random coefficient model was generated (equation (2)), which fit the data significantly better as measured by the log likelihood:

$$LEB_i = \beta_{0i} + \beta_{1i} * logGDPpc_i + \varepsilon_i \quad (2)$$

However, equation (2) will not account for the observed curvature in Figure 2. Thus a set of higher order polynomial models was generated iteratively (equations (3) – (7):

$$LEB_i = \beta_{0i} + \beta_{1i} * logGDPpc_i + \beta_2 * log^2GDPpc_i + \varepsilon_i \quad (3)$$

$$LEB_i = \beta_{0i} + \beta_{1i} * logGDPpc_i + \beta_{2i} * log^2GDPpc_i + \varepsilon_i \quad (4)$$

$$LEB_i = \beta_{0i} + \beta_{1i} * logGDPpc_i + \beta_2 * log^2GDPpc_i + \beta_3 * log^3GDPpc_i + \varepsilon_i \quad (5)$$

$$LEB_i = \beta_{0i} + \beta_{1i} * logGDPpc_i + \beta_{2i} * log^2GDPpc_i + \beta_3 * log^3GDPpc_i + \varepsilon_i \quad (6)$$

$$LEB_i = \beta_{0i} + \beta_{1i} * logGDPpc_i + \beta_2 * log^2GDPpc_i + \beta_3 * log^3GDPpc_i \ \beta_4 * log^4GDPpc_i + \varepsilon_i \quad (7)$$

Model	1	1	2	2	3	3	3	4	5	5	6	7
LogLikelihood	-15653	-15592	-14342	-14274	-14283	-14237	-14148	-14100	-14222	-14128	-14012	-14127
random intercept ($\beta 0_i$)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
random logGDPpc ($\beta 1_i$)			(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
random logGDPpc^2 ($\beta 2_i$)								(+)			(+)	
omit logGDPpc < 4.5		(+)		(+)		(+)	(+)	(+)		(+)	(+)	(+)
omit UAE							(+)	(+)		(+)	(+)	(+)
logGDPpc	7.953***	8.064***	10.201***	10.167***	41.603***	36.427***	35.245***	37.073***	95.468***	108.541***	50.085	170.660***
	[47.107]	[47.019]	[8.203]	[8.146]	[13.163]	[11.123]	[10.565]	[3.060]	[8.515]	[9.244]	[1.484]	[3.238]
(logGDPpc)^2					-2.254***	-1.884***	-1.796***	-2.024**	-10.029***	-12.002***	-3.894	-25.290**
					[-10.917]	[-8.723]	[-8.107]	[-2.294]	[-6.692]	[-7.569]	[-0.854]	[-2.280]
(logGDPpc)^3									0.363***	0.460***	0.090	1.690*
									[5.472]	[6.483]	[0.421]	[1.661]
(logGDPpc)^4												-0.042
												[-1.213]
Constant	4.400***	3.612***	-10.000	-9.776	-121.809***	-103.309***	-99.424***	-101.021**	-242.284***	-270.646***	-131.232	-376.534***
	[3.354]	[2.710]	[-1.215]	[-1.184]	[-9.054]	[-7.528]	[-7.170]	[-2.402]	[-8.419]	[-9.086]	[-1.536]	[-4.063]
Observations	5,203	5,190	5,203	5,190	5,203	5,190	5,153	5,190	5,190	5,153	5,153	5,153
Number of groups	125	125	125	125	125	125	124	125	125	124	124	124

Table 1. Iterative fittings of base models. Models 1, 2, 3, and 5 were all fitted with and without outliers. Z-statistics are shown in brackets. *** p<0.01, ** p<0.05, * p<0.1

In some of these models (equations (4) and (6)) we allowed not only the slope of logGDPpc to vary, but also the slope of log^2GDPpc (denoted by β_{1i} and β_{2i}, respectively) , to account for the possibility that different countries would have different curvatures. We aimed to optimize our base model by

selecting the one with the log likelihood closest to zero and all parameters in the model significant at the $p < .05$ level. Based on these criteria, we chose equation (4) as our base model, permitting both the slope of logGDPpc and $\log^2$GDPpc to vary by country. On application to several countries (data not shown), this model appears to be the best parsimonious fit.

Variable Testing

Having settled on equation (4), we tested our indicators of interest for their effect on the trajectory of the Preston curve. Since our hypothesis was that these would change the rate at which a country's life expectancy would increase for a given increase in GDP, we generated a multilevel model in which these indicators contributed not only to predicted life expectancy but also to the random coefficient on the slope of logGDPpc and $\log^2$GDPpc (equation (8)). In notation, this can be written modifying equation (4) and adding a term for our variable of interest (Z):

$$LEB_i = \beta_{0i} + \beta_{1i}*\text{logGDPpc}_i + \beta_{2i}*\log^2\text{GDPpc}_i + \beta_3*Z_i + \varepsilon_i \quad (8a)$$

where:

$$\beta_{0i} = \gamma_{00} + \xi_i \quad (8b)$$

$$\beta_{1i} = \gamma_{10} + \gamma_{11}*Z + \mu_i \quad (8c)$$

$$\beta_{2i} = \gamma_{20} + \gamma_{21}*Z + \delta_i \quad (8d)$$

In the reduced form, equation (8) can be written using a series of interaction terms:

$$LEB_i = \gamma_{00} + \beta_3*Z_i + (\gamma_{10} + \mu_i)*\text{logGDPpc}_i + (\gamma_{11}*Z)*\text{logGDPpc}_i + (\gamma_{20} + \delta_i)*\log^2\text{GDPpc}_i + (\gamma_{21}*Z)*\log^2\text{GDPpc}_i + \xi_i + \varepsilon_i \quad (8e)$$

In words, each coefficient can be described as:

- β_{0i}: the intercept in country *i*'s production function for LEB by logGDPpc, differing from the average value γ_{00} by ξ_i
- β_{1i}: the slope in country *i*'s production function for LEB by logGDPpc; not only randomized but altered by $\gamma_{11}*Z$, and differing from the average value γ_{10} by μ_i
- β_{2i}: the curvature in country *i*'s production function for LEB by logGDPpc; not only randomized but affected by $\gamma_{21}*Z$, and differing from the average value γ_{20} by δ_i
- β_3: the elasticity of LEB with respect to a one unit change in Z

In equation (8a), β_{1i} is the dominant term in determining how quickly life expectancy in country *i* rises in response to a given increase in logGDPpc. β_{2i} tends to be much smaller and only affects the curvature of the country-specific Preston curve.

Variable Results

Tables 2-3 show the results. Of the eleven identified variables, three (educational expenditures as a percent of GDP, out-of-pocket spending as a percent of total health spending, and proportion of community health workers per population) did not have enough data for to carry out our analysis. Five variables show a significant interaction with logGDPpc; three show non-significant interactions. There is significant regional variation as well, as suggested by the qualitative analysis; Asian and African countries show a steeper increase in health for given life expectancy than average.

An increase in total fertility rate (TFR, the average number of expected births per woman) is associated with not only worse health, but slower rise in life expectancy for a unit increase in logGDPpc.

A one unit rise in TFR, all other things being constant, results in a decrease in LEB of 3-4 years, depending on the level of GDP. This results from a 5.1% decrease in the slope of logGDPpc (3.22/63.31 = .051; the contribution of the quadratic term is negligible). In other words, a 1 unit increase in TFR means that the same GDP per capita will yield 5% less health.

The same detrimental effect on the Preston curve can be seen for increasing percent of GDP accounted by oil rents, defined as the difference between the value of crude oil production at world

Log Likelihood	-13825	-12634	-4046	-4500	-3409	-2508	-4256
Model	(4)	(8)	(8)	(8)	(8)	(8)	(8)
Z	Base model	TFR	logdocs10000	logHIV	healthExpTot	feduc	logoil
logGDPpc	36.120***	63.313***	13.688**	12.963	22.026***	18.160***	31.677**
	[2.866]	[4.187]	[2.087]	[1.581]	[3.577]	[2.599]	[2.382]
(logGDPpc)^2	-1.976**	-4.583***	-0.624	-0.404	-1.057**	-1.043**	-1.516*
	[-2.142]	[-3.930]	[-1.276]	[-0.684]	[-2.505]	[-1.983]	[-1.669]
TFR		7.944***					
		[4.671]					
intTFR		-3.219***					
		[-6.637]					
int2TFR		0.234***					
		[6.825]					
logdocs10000			-14.462***				
			[-2.609]				
intlogdocs10000			4.703***				
			[2.964]				
int2logdocs10000			-0.305***				
			[-2.725]				
logHIV				21.833***			
				[4.393]			
intlogHIV				-5.719***			
				[-3.807]			
int2logHIV				0.354***			
				[3.197]			
healthExpTot					1.437**		
					[2.022]		
inthealthExpTot					-0.279		
					[-1.313]		
int2healthExpTot					0.016		
					[1.041]		
feduc						-0.656	
						[-0.138]	
intfeduc						1.072	
						[0.788]	
int2feduc						-0.061	
						[-0.639]	
logoil							7.861**
							[2.265]
intlogoil							-2.067**
							[-2.111]
int2logoil							0.134**
							[1.965]
Constant	-96.712**	-144.995***	-7.823	-8.597	-39.945*	-26.814	-86.570*
	[-2.222]	[-2.897]	[-0.359]	[-0.303]	[-1.791]	[-1.161]	[-1.776]
Observations	5,110	5,108	1,450	2,053	1,863	882	1,671
Number of groups	123	123	122	96	122	92	56

z-statistics in brackets

*** p<0.01, ** p<0.05, * p<0.1

Table 2. Variables which may change rapidly in any given country. TFR = Total Fertility Rate, logdocs10000 = log (physicians per 10,000 population), logHIV = log(HIV prevalence), heatlhExpTot = % GDP spent on health care, feduc = expected years of female education, logoil = log (oil rents as a % of GDP). Int"var" indicates the interaction term with logGDPpc, int2"var" for $\log^2$GDPpc.

Log Likelihood	-13825	-12025	-13328	-13818	-13817	-13821	-13825
Model	(4)	(8)	(8)	(8)	(8)	(8)	(8)
Z	Base model	logpop	logarea	asiamainland	africamain	latin	MENA
logGDPpc	36.120***	150.248***	24.473	37.677***	35.270***	50.775***	37.564***
	[2.866]	[-6.783]	[0.402]	[3.026]	[2.670]	[3.532]	[2.759]
(logGDPpc)^2	-1.976**	9.770***	-1.267	-2.069**	-1.983**	-3.182***	-2.122**
	[-2.142]	[6.018]	[-0.293]	[-2.276]	[-2.089]	[-3.002]	[-2.125]
logpop		-35.066***					
		[-8.910]					
intlogpop		12.578***					
		[11.133]					
int2logpop		-0.823***					
		[-10.373]					
logarea			-3.385				
			[-0.186]				
intlogarea			0.719				
			[0.141]				
int2logarea			-0.043				
			[-0.118]				
asiamainland				-117.006			
				[-1.494]			
intasiamainland				40.503*			
				[1.799]			
int2asiamainland				-3.282**			
				[-2.000]			
africamain					-102.858		
					[-1.535]		
intafricamain					32.738*		
					[1.705]		
int2africamain					-2.685*		
					[-1.931]		
latin						115.212	
						[1.094]	
intlatin						-41.190	
						[-1.387]	
int2latin						3.496*	
						[1.651]	
MENA							13.043
							[0.107]
intMENA							-7.334
							[-0.209]
int2MENA							0.773
							[0.304]
Constant	-96.712**	439.146***	-44.665	-103.423**	-90.475*	-140.124***	-99.677**
	[-2.222]	[5.844]	[-0.206]	[-2.397]	[-1.950]	[-2.844]	[-2.123]
Observations	5,110	5,110	4,948	5,110	5,110	5,110	5,110
Number of groups	123	123	123	123	123	123	123

z-statistics in brackets

*** p<0.01, ** p<0.05, * p<0.1

Table 3. Variables which change slowly for a given country or not at all. logpop = log(population), logarea = log (land area in km^2), asiamainland = dummy variable for mainland Asia (excluding middle east), africamain = dummy variable for sub-Saharan Africa mainland, latin = dummy variable for Latin America, MENA = dummy variable for middle east/north Africa. Int"var" indicates the interaction term with logGDPpc, int2"var" for log^2GDPpc.

prices and total costs of production, and for increasing HIV prevalence . A doubling of HIV prevalence results in 0.5 years less of LEB by attenuating the relationship between GDPpc and LEB. A doubling of oil rents as a percentage of GDP results in a 4.5% decrease in a country's ability to convert wealth to GDP (log(2)*2.07/31.68 = .045), although this is nearly made up for by the increase in total wealth, as a doubling of oil rents leads to only a 0.1 year decrease in LEB. However, another way of interpreting this

result is to notice that a doubling oil revenues as a percentage of GDP has no positive impact on overall population health, despite the fact that it was usually correlated with overall growth of GDPpc, which would imply that none of the benefits of this newly exported oil is reaching the population of oil-producing nations on average. Rather, the oil wealth may be merely enriching those with access to oil wealth while not in any way boosting health infrastructure.

Our data also indicate that there are investments that can augment a country's ability to transform wealth into health. A doubling of the number of doctors in the country leads to a 24% increase in the slope of logGDPpc (log(2)*4.7/13.68 = .24) with a gain of LEB between 2-3 years, depending on GDP.

Health expenditure as a percentage of GDP and years of female education do not significantly shift the Preston curve in our full model.

Similar calculations can be made for the other indicators which are less likely to change over time (Table 3). For example, a large population appears to be related to a faster Preston transition, although this is possibly confounded by the overrepresentation of fast-growing Asian countries with large populations. Indeed, Asian countries show a faster than average Preston ascent, as, surprisingly, do sub-Saharan African countries. Latin American countries and middle east/north African countries (MENA) do not show a significant deviation from the average developing country Preston curve. Controlling for time (data not shown), however, eliminates these regional differences. Indeed, Africa's "success" could just as easily be due to her slow economic growth, while new technologies are taken up to nevertheless improve health (13).

Discussion

This work was undertaken to quantitatively describe the different factors that might be associated with a faster or slower Preston ascent. However, whereas qualitative appreciation of different Preston trajectories might seem to indicate that geography is destiny, in that many different countries from the same region showed remarkably similar Preston curves, we also found other factors that contribute to significantly faster or slower mortality transitions. Indeed, our most significant finding, if not entirely unexpected, is the relationship between decreasing TFR and increasing conversion of economic growth into population health. Indeed, the Bangladeshi miracle of rapidly decreasing TFR and improving health is not limited to this one country, but is in fact a pattern common to many other developing countries. This implies that one of the best investments a country may be in a robust family planning program, as has been demonstrated from Bangladesh to Iran to Brazil.

This analysis also revealed other factors which have been less reliably linked to population health, that is, dependence on oil revenues and large population. While the 'Dutch Disease' is a well-known economic malady, it also seems to directly harm the health of the populations afflicted. Indeed, in a taxonomy of Preston, oil rich countries consistently underperform for a given level of GDP. In Central Africa, for example (Figure 3), those countries dependent on oil (Angola, Equatorial Guinea, Gabon, Republic of Congo, and Democratic Republic of Congo) have done much worse at improving their population's health than have Uganda and Rwanda despite a GDPpc of 2-24 times higher.

The link between differential Preston trajectories and region and population size has implications for goal setting. As the world begins to take account of global progress toward the health MDGs, it is worth taking into consideration why so many countries will fail to meet them. Our analysis indicates some endemic factors such as region, small population size, HIV prevalence, TFR, dependence on commodities and inadequate supply of doctors—which all apply to most countries in sub-Saharan Africa—likely renders these goals extrapolated from China and Vietnam inappropriate, and indeed set many countries up to fail. The analysis put forward in this paper permits the identification of the best possible performance for a given set of indicators, while also highlighting policies that are most effective at shifting countries between slower and faster Preston curves. Furthermore, since the list of indicators

we surveyed here was by no means exhaustive, it is likely that there are other important determinants of health trajectory that wait to be discovered. Table 4 summarizes our findings regarding which variables are associated with a shift to a faster or slower Preston ascent.

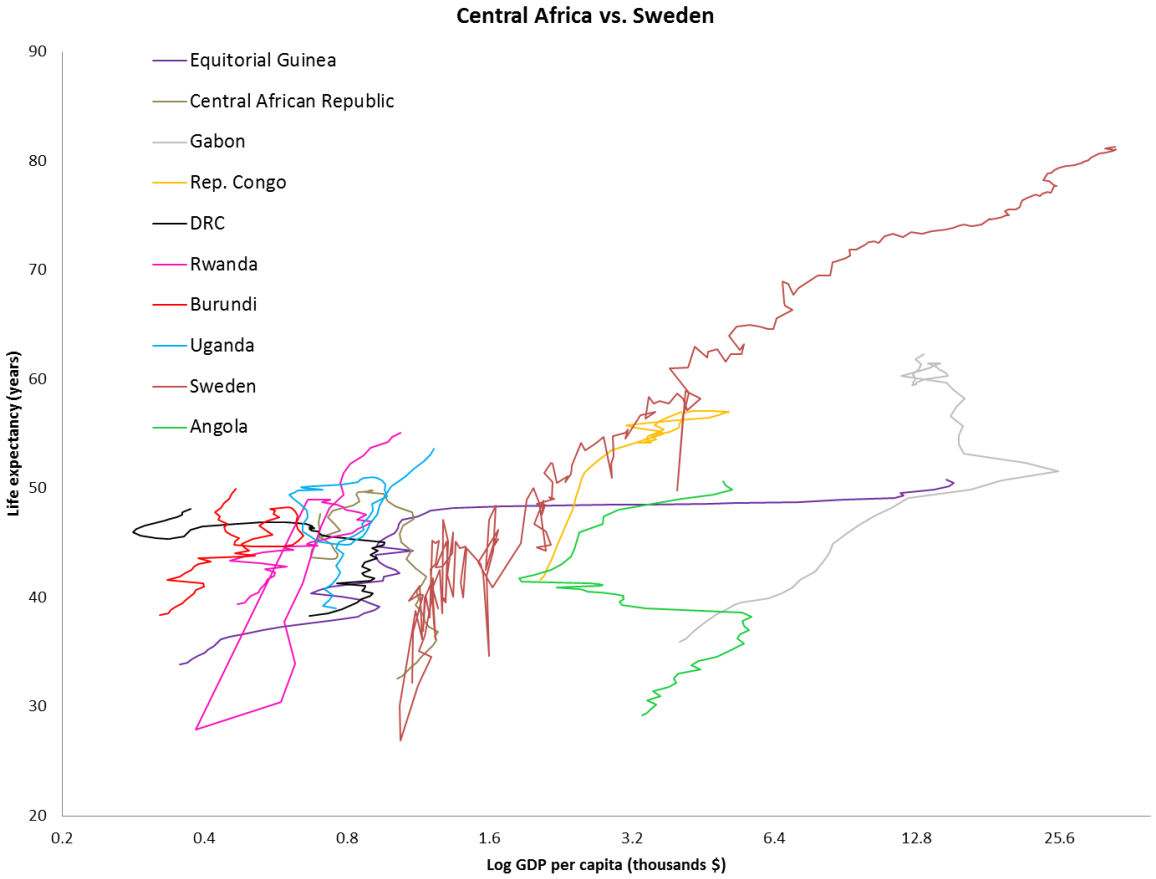

Figure 3. Central Africa demonstrates how increased oil rents are associated with a significantly underperforming Preston curve.

This work has several limitations. Firstly, limited data was available for many countries; the path of many countries before 1990 could not be evaluated. However, most developing countries enter our dataset while LEB was still below 50, meaning that we were able to observe a significant amount of their mortality transition. Secondly, our model was quite complicated, varying the slope of both logGDPpc and $\log^2$GDPpc. This complexity required a large amount of data to find significant relationships and so may have yielded potentially insufficient power to detect Preston shifters. For example, years of female education has previously found to be strongly associated with decreasing infant mortality (13). While the sign of the coefficient for intfeduc (Table 2) is consistent with such a finding, the fact that data was only available for barely 50% of country-years may have rendered this association insignificant. Thirdly, we did not yet control for the fact that rates of Preston ascent may simply vary over time, as has been noticed previously (13), although we will undertake this analysis soon. Preliminary results indicate that the relationship for TFR is robust, but not for logdocs10000 (data not shown), again possibly due simply to lack of sufficient power. Finally, we are not able to measure causality in this analysis. It is true that the interaction terms do indicate a relationship between decreasing TFR and an increased speed of converting wealth into health, but there remains the possibility that increasing wealth could be interacting with TFR through other unmeasured variables.

Indicators positively associated with quicker Preston ascent
Prevalence of physicians
Population
Asia mainland
Africa mainland
Indicators not significantly associated with differential Preston ascent
% of GDP spent on health care
Years of female education
Latin American
Middle East/North Africa
Land size (area)
Indicators negatively associated with quicker Preston ascent
TFR
HIV prevalence
Oil rents as % of GDP

Table 4. Summary of Results.

Conclusion

Our analysis shows that the canonical logarithmic Preston curve relationship hides substantial heterogeneity in historical trajectories that can be observed and exploited by systematically analyzing individual growth curves. Our approach has allowed new insight into superior and inferior performance, and many other factors which may contribute to this differentiation likely remain undiscovered. From a policy perspective, our analysis empowers readers to hold governments accountable for connecting economic improvements to improvements in population health. Once readers know how a given country has been performing relative to standard benchmarks they can ask about policy reforms that can explain and improve performance.

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