Adaptation to Climate Change:
Evidence from 18th and 19th Century Iceland [§]

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ABSTRACT: We investigate the effect of climate change on population growth in 18th and 19th century Iceland. We find that annual temperature changes help determine the population growth rate in pre-industrial Iceland: a year 1°C cooler than average drives down population growth rates by 0.57% in each of the next two years, for a total effect of 1.14%. We also find that 18th and 19th century Icelanders adapt to prolonged changes in climate: these adaptations take about 20 years and reduce the short run effect of annual change in temperature by about 60%. Finally, we find that a 1°C sustained decrease in temperature decreases the steady state population by 10% to 26%.

Key words: Climate change, Climate adaptation, Iceland.

JEL classification: Q54, Q01, N54.

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1. Introduction

We analyze time series describing climate and population in 18th and 19th century Iceland. We investigate the impact of climate on population growth rates and the ability of 18th and 19th century Icelanders to adapt to changes in climate.

Our analysis rests on primarily on two types of data. The first is annual population data dating back to 1735. The second is imputed annual temperature data dating back to the late 1600's. We construct these data from measured temperature data and annual records of the ratio of the concentration of Oxygen-18 to Oxygen-16 in ice core strata from nearby Greenland. The resulting long time series of population and annual temperature data allow an explicit analysis of short run and long run responses to climate change. In addition, we are able to check whether a short run climate shock has a different effect when it follows a cold history than when it follows a warm history. This gives us a direct and formal statistical test of a commonsense notion of 'adaptation'. By repeating this test for different definitions of 'shock' and 'history', we trace out the rate of adaptation and the time-frame over which it occurs.

We find that annual temperature changes help determine the population growth rate in pre-industrial Iceland: a year 1°C cooler than average drives down population growth rates by 0.57% in each of the next two years, for a total effect of 1.14%. We also find that 18th and 19th century Icelanders adapt to prolonged changes in climate: these adaptations take about 20 years and reduce the short run effect of annual change in temperature by about 60%. Finally, we find that a 1°C sustained decrease in temperature decreases the steady state population by 10% to 26%.

Back of the envelope calculations suggest that about 400 million people live in countries where per capita income is at or below late 19th century Iceland's. We currently have little basis for anticipating the effects that global warming will have on these populations. In particular, we have little basis for estimating the size or time path of climate induced population changes from mortality or migration, nor the ultimate ability of these population to adapt to climate change. Given the likelihood of continued warming, these are policy questions of first order importance. To the extent that poor contemporary populations respond to adverse changes in climate like 18th and 19th century Icelanders, our results inform these policy questions.

2. Literature

Much previous research on human response to climate change can be roughly grouped into three classes. The first examines the relationship between cross-sectional variation in climate and an outcome of interest. For example Mendelsohn, Nordhaus, and Shaw (1994) examines the relationship between agricultural land prices and climate using cross-sectional data. Reductively, they compare the price of a farm in the South with one in the North and attribute the difference to climate. The second class of research examines short run variation in weather to infer response to climate change. For example, Deschenes, Greenstone, and Guryan (2009) looks at the relationship between daily weather data and birth weight to estimate the effects of climate change on birth weight. By construction, neither methodology reveals the rate at which people respond and adapt to climate change. The third class of research examines relationships between long time series of climate and the outcome variable of interest. For example, Campbell (2009) argues that changes in climate caused the onset of plagues in medieval Europe, but does not examine adaptation. Galloway (1986), Zhang, Brecke, Lee, He, and Zhang (2007) and Polyak and Asmerom (1986) each examine long time series of low frequency climate data and various outcome variables, but do not examine the rate at which people respond or adapt to changes in climate.

Perhaps the nearest relatives to our research are Dell, Jones, and Olken (2008), Hornbeck (2009), and Olmstead and Rhode (2010), each of which is explicitly concerned with adaptation to climate change. Dell *et al.* (2008) consider a panel of countries for which they record 50 years of annual GDP and climate data. Like us, they are explicitly interested in the rate at which economies respond to climate changes and the extent of adaptation. However, to measure adaptation they exploit cross-sectional variation in their sample: they compare long differences in growth rates and climate across-countries. While our finding of a large response to climate change in a poor country is broadly consistent with their results, our investigation of adaptation relies solely on time series variation in our data. Olmstead and Rhode (2010) examine the extension of US agriculture into progressively less favorable climates from 1839 to 2002. Like Mendelsohn *et al.* (1994) they exploit only cross-sectional variation in climate, but by following locations over time are able to make inferences about the rate at which improvements in technology allow farmers to overcome adverse conditions. Where Olmstead and Rhode (2010) examine the extent to which technological improvement can compensate for changes to climate, (as we argue below) we investigate the extent of adaptation in an environment where technology is more nearly constant. This relieves us of the concern that technological progress is affecting outcomes through some channel other than by facilitating adaptation to climate change. Finally, Hornbeck (2009) examines the evolution of US agriculture in the aftermath of the dust bowl. These are essentially the same questions we address, however, Hornbeck (2009) looks at the implications of a one time event, the dust bowl, while we look at the implications of ongoing changes in climate. Like Hornbeck (2009), we find that population changes are an important margin of adjustment to environmental change.

3. Data

To learn about short-run responses and long-run adaptations to climate change we require data satisfying three conditions. They must describe a period long enough to observe climate change. They must be at a high enough frequency to describe population responses. They must allow us to distinguish the relationship between climate and population from confounding trends, economic growth and migration in particular.

During the 18th and 19th century migration to and from Iceland was low, and government policy actively discouraged in-migration (Karlsson, 2000). Statistics Iceland (2010) tracks net migration from 1801 onward. Over the period 1801-1860, when the population level was about 50,000, mean net migration was -17 people/year. Moreover, Iceland was remarkably insulated from technical progress (Eggertsson, 1994). During the 18th and early 19th century, there was very little manufacturing. Roads allowing wheeled carts were not built until nearly 1900 (Karlsson, 2000). In 1801, Reykjavik had a population of only 307 and only about 10% of calories consumed in 18th century Iceland were derived from fish (Karlsson, 2000).

In sum, 18th and 19th century Iceland was overwhelmingly employed in raising livestock and the hay to feed them, and was as insulated from migration and technological progress as can be hoped. Data describing Icelandic climate and population during this period should reveal a relationship between climate and population (if one exists), and we can reasonably expect to distinguish this relationship from population trends caused by technological progress and migration.

A. *Population Data*

Estimates of Iceland's population are available back to the middle ages (see e.g. Steffensen (1963)). However, prior to 1703 these estimates are speculative. We restrict attention to the population data available from the annual surveys provided by Statistics Iceland (2010) from 1734 to the present.[1]

Most of our estimations rely on the period ending in 1860. We have three reasons for choosing this terminal date. First, the top panel of figure 1 shows that the rapid 20th century increase in Iceland's population level was only beginning at this time. Second, the middle panel of figure 1 shows no trend in the population growth rate during this period. Third, in results reported below, the estimated effect of climate on the population growth rate is robust to the inclusion of a quadratic in time and to changing the end of the study period to 1820 or 1880. We conclude that for a study period ending in 1860 we are unlikely to confound the effects of latent technological change with the effect of climate on population.

We note that Iceland was subject to two catastrophic decreases in population during our study period. These events are clearly visible in the top two panels of figure 1. The earlier of the two occurred from 1756 to 1758 and was the result of a volcanic eruption which poisoned pasture land and led to famine. The second, which occurred from 1758 to 1786 was the result of plague (Karlsson, 2000). Testing indicates that the precise choice of which years to control for is not important, but controlling for these two catastrophes does improve the accuracy of our estimations. Thus, throughout the paper, our population data consists of the Statistics Iceland annual population survey results from 1734–1860, excluding (i.e., adding dummy variables to control for) the years 1756–1758 and 1784–1786.

B. *Temperature Data*

There are five Icelandic weather stations which record temperatures from the late 1800's onward (Goddard Institute for Space Studies, 2010); Akureyri, Reykjavic, Stykkisholmur, Teigarhorn, and Vestmannaeyja. The series from a sixth station, Grimsey, is less complete. The Vestmannaeyja station is on a small lightly populated island off the southern coast of mainland Iceland and is not well correlated with the others. Thus, we take the "true" Icelandic temperature to be the average of the measured temperatures at the four weather stations, i.e. at Akureyri, Reykjavic, Stykkisholmur, and Teigarhorn (figure 2).

[1] We ignore a single extensive survey conducted in 1703 because our econometric analysis requires consecutive years of data.

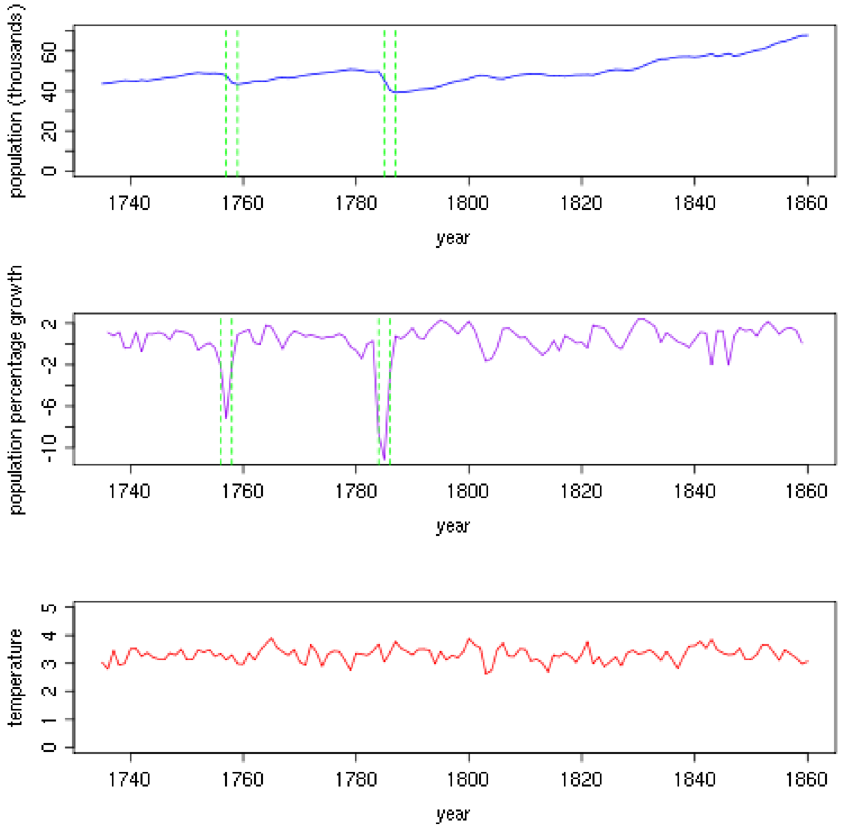


Figure 1. Iceland's total population (top), annual percentage population change (center) and imputed mean annual temperature in degrees Celsius (bottom). Excluded volcano-related periods delimited by dashed green lines in the top two panels. All figures describe the period 1735 – 1860.

Our analysis requires temperature data pre-dating available measured temperatures. To overcome this obstacle, we impute historical temperatures from heavy-oxygen delta ice core values, $\delta^{18}O$. Heavy-oxygen delta ice core values measure fractional deviation of the ratio of the concentration of Oxygen-18 to Oxygen-16 in ice core strata as compared to that in standard mean ocean water. Since this isotope ratio varies systematically with temperature, and since ice core strata can be accurately dated, ice core $\delta^{18}O$ is widely used as a proxy for historical temperatures.[2]

Ice core data are not available within Iceland. However, there are four long-term ice core data sets available from nearby Greenland; Crete, Millicent, Camp Century, and Dye2 (National Climatic Data Center, 2010). To construct our measure of historical temperature we predict measured temperature as a function of contemporaneous and lagged $\delta^{18}O$ values from the four ice core series. We then use these estimates to impute temperatures to 18th and 19th century Iceland using the much longer ice core time series.

Table 1 presents a few of these estimations. In each of these regressions, the dependent variable is the annual average of measured temperatures at the Akureyri, Reykjavic, Stykkisholmur, and

[2]We note that while many types of proxies are available (see e.g. Thompson, Davis, and Mosley-Thompson (1994), Bruckner (2010), and the references therein), the most reliable reconstructions are based upon ice core data.

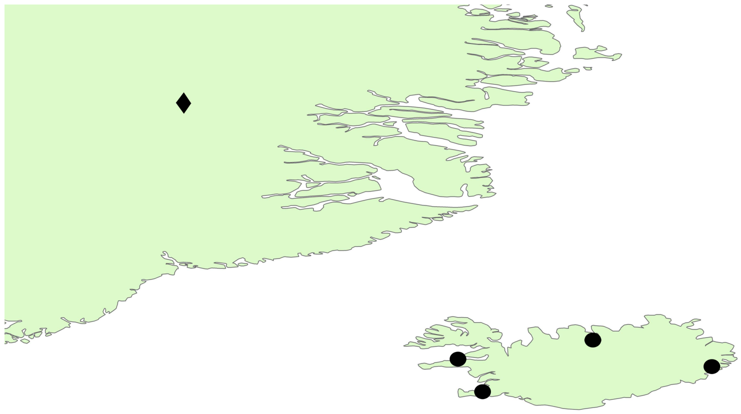


Figure 2. Map of Iceland and Greenland. Circles indicate the locations of the Akureyri, Reykjavic, Stykkisholmur, and Teigarhorn weather stations. The Crete ice core location is indicated by a diamond.

Table 1. Predicted temperature regressions.

	(1)	(2)	(3)	(4)	(5)
Crete $\delta^{18}O$	0.239***	4.255*		0.279***	0.319***
	0.07	2.282		-0.09	0.07
(Crete $\delta^{18}O$)^2		0.06*			
		0.03			
Millicent $\delta^{18}O$			0.195***	0.06	
			0.06	0.07	
Constant	12.25	81.09**	9.879***	15.37***	15.02***
	2.29	39.16	1.86	2.42	2.38
N	74	74	67	67	67
R^2	0.15	0.19	0.13	0.25	0.24

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1.

Teigarhorn weather stations. Column 1 presents the linear Crete specification. This regression includes only a linear term in the Crete $\delta^{18}O$ values and a constant. Column 2 presents the quadratic Crete specification. This regression adds a quadratic term in the Crete $\delta^{18}O$ values. We see that the R^2 increases slightly, but the precision with which we estimate coefficients is lower. Column 3 presents the linear Millicent specification. This regression predicts measured temperature as a linear function of the Millicent $\delta^{18}O$ values. This regression is similar to linear Crete, but has a marginally lower R^2. Note that the Millicent icecore ends in 1967 rather than 1974 for Crete. Thus, the linear Millicent regression of column 3 is based on 67 annual observations years as opposed to 74 for linear and quadratic Crete. Column four conducts a 'horse race' between the Millicent and Crete icecores. We see that the Crete $\delta^{18}O$ values are statistically significant and the Millicent values are not. From this, together with the higher R^2 in linear Crete than linear Millicent, we conclude that Crete is a better predictor of measured temperature than is Millicent.

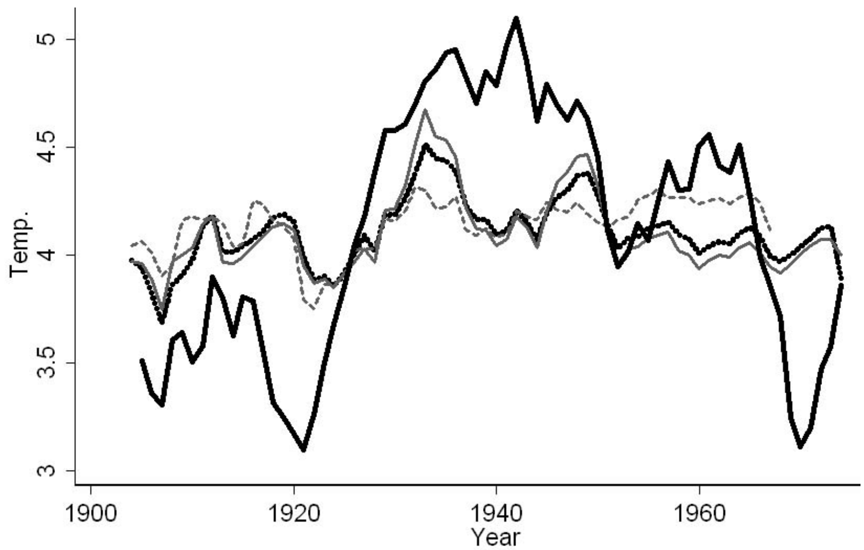


Figure 3. Observed and predicted five year moving average temperatures for 20th century Iceland, including average measured temperature (thick solid line), linear prediction from Crete ice core as in (1) (medium dotted), quadratic prediction from Crete ice core (solid grey), and linear prediction from Millicent ice core (dashed grey).

The horse race specification of column 4 of table 3 has a higher R^2 than the preceding specifications. This suggests that we consider using both series to construct our historical temperature. In fact, in column 5 we restrict the specification of column 1 to the slightly smaller sample of columns 4 and 5. We see that, on this sample, Crete has more explanatory power than on the larger sample. The higher R^2 in the shorter sample reflects the fact that the longer measured temperature sequence is more was variable than is the shorter sequence.[3]

Our preferred regression in table 3 is column 1.[4] This regression is able to exploit the larger sample, is based on coefficients that are precisely estimated, and are fairly stable across the specifications reported in columns 1, 4 and 5. The bottom panel of figure 1 plots this temperature series over the course of our 1735-1860 study period.

With this said, the case for preferring linear Crete imputed temperatures to linear Millicent or quadratic Crete is weak. Indeed, in figure 3 we plot all three predicted temperature series and the underlying measured temperature from about 1900 on. They are quite similar. Given this, while most of our analysis is based on linear Create imputed temperature, we will check that our findings are robust to using the linear Millicent and Quadratic Crete imputations.

[3]In addition to the regressions reported in table 3 we also experimented with the Dye2 and Century ice core data, and with lagged and higher order terms of the various icecores. These variables did not have a robust ability to predict measured temperature and we do not report these results.

[4]Our preferred temperature proxy actually uses more precision than is reported in table 3. In particular, our preferred temperature proxy is the best fitted linear transformation:

$$\text{temperature} = 12.25068 + 0.2389029 * (\text{Crete}\delta^{18}O)\,. \tag{1}$$

4. Notation and estimation strategy

We begin with notation to describe population change, weather and climate.

Our outcome variable is annual percentage population change,

$$(\Delta pop)_t \ := \ \frac{pop_{t+1} - pop_t}{pop_t} \times 100\% \,, \tag{2}$$

where pop_t is thousands of total population recorded on January 1 in year t. As already noted, we exclude six specific years with large volcano and plague related population decreases.

We denote the current year's estimated average temperature by $temp_t$, the previous year's temperature by $temp_{t-1}$, and kth lag of temperature by $temp_{t-k}$. We also investigate the effects of moving averages of previous years' temperatures, e.g., $\text{MA}2_t := \frac{1}{2}(temp_{t-1} + temp_{t-2})$, or more generally,

$$\text{MA}j_t := \frac{1}{j}(temp_{t-1} + \ldots + temp_{t-j})\,.$$

We also consider lagged moving average temperatures:

$$\text{MA}j_{t-i} := \frac{1}{j}(temp_{t-i-1} + \ldots + temp_{t-i-j})\,.$$

To ease exposition, we "demean" all temperature variables by subtracting off their mean over the entire extended time range 1730–1880.

We estimate variants of the following equation,

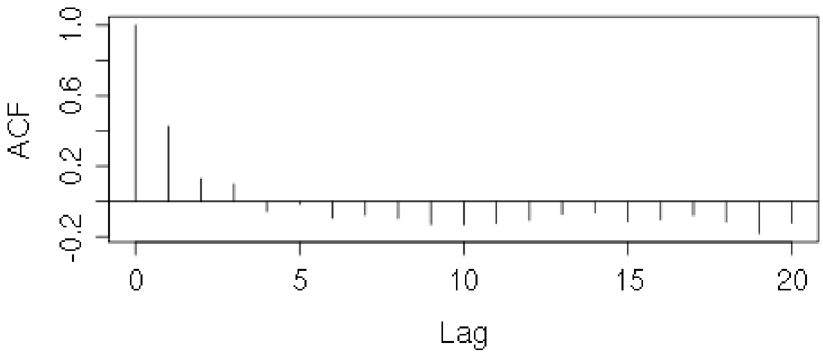
$$(\Delta pop)_t = A_0 + f(temp_t,..,temp_{t-50}) + \text{Controls} + \epsilon_t, \tag{3}$$

where f is a function of temperature variables that varies across specifications and may include lagged values, moving averages, lagged moving averages, or interaction terms.

To distinguish the effects of climate on population from the effect of unobserved confounding trends, our estimations include *time* and its square, $time^2$ as control variables, where *time* is defined as $year - 1734$. To allow for effects of current population on population growth (e.g. due to resource constraints), we also control for pop_t. To account for unmeasured slowly-changing latent variables, e.g., a high percentage of women of child-bearing age, which create similarities between Δpop for adjacent years, we control for the previous year's percentage growth, $(\Delta pop)_{t-1}$.

By estimating equation (3) we hope to learn the nature of f, the function that describes the relationship between climate and population growth rates. Before turning to our estimates, we discuss the potential problems faced by such an estimation.

Time series regressions based on series which exhibit unit roots require different techniques than those we use here. To test for unit roots, we run the Dickey-Fuller test on the time series $(\Delta pop)_t$. This test rejects the unit root null hypothesis at the 0.01 level for the standard Dickey-Fuller test, and at the 0.015 level for the extended Dickey-Fuller test. We conclude that $(\Delta pop)_t$ does not have a unit root and hence standard regression analysis is appropriate. It follows that we also do not need to consider the possibility of co-integration.



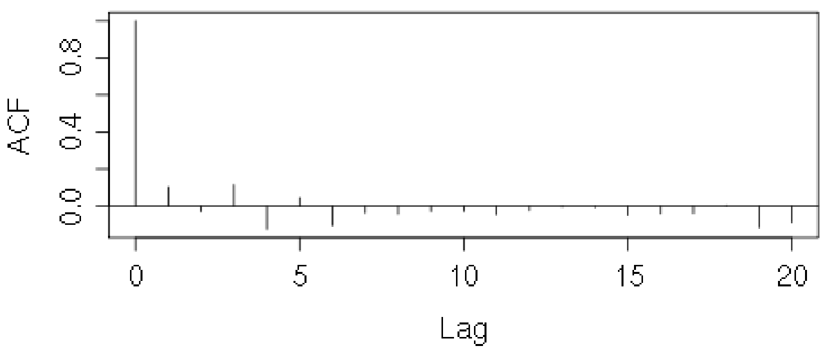


Figure 4. Auto-correlation function (ACF) for regression residuals for table 3 column 4, either omitting (top) or including (bottom) the quantity $(\Delta pop)_{t-1}$ as an explanatory variable.

Our regressions include many explanatory variables which are serially correlated, e.g. $\mathrm{MA}10_t$ and $\mathrm{MA}10_{t-1}$ have strong dependence. This alone does not affect OLS coefficient estimates. However, serial correlation of regressors suggests the possibility that the regression's residual errors are serially correlated. If true this affects the calculation of standard errors.

One way to reduce serial correlation of residuals is to include as an explanatory variable the previous year's outcome variable, i.e. $(\Delta pop)_{t-1}$, as we do in many of our regressions.

Figure 4 presents our calculation of the auto-correlation function (ACF) for the residual values of for table 3 column 4 either omitting (top) or including (bottom) the $(\Delta pop)_{t-1}$ explanatory variable. As expected, the serial correlation is reduced with the inclusion of $(\Delta pop)_{t-1}$, but the serial correlation is small in either case, except that the lag one autocorrelation is significantly positive when $(\Delta pop)_{t-1}$ is not included as a regressor.

While figure 4 suggests that auto-correlation is not important to our analysis, provided we control for lagged $(\Delta pop)_{t-1}$, since correct standard errors are crucial to our investigation, we considered alternative formulae for regression standard errors. In particular, we experimented with robust standard errors, Newey-West corrected errors, and Prais-Orcutt models. Since OLS with Newey-West corrected errors has better asymptotic properties than the others, we prefer this specification, and tables 2 and 3 present only Newey-West corrected errors.[5]

[5] Newey-West standard errors require choosing the truncation parameter m, corresponding to the number of terms to sum in the autocovariance series. For this, we used the general default rule (e.g. Stock and Watson (2007), eqn (15.17)),

$$m \;=\; \mathrm{round}(0.75 * samplesize^{1/3}) \;\doteq\; \mathrm{round}(0.75 * 125^{1/3}) \;=\; \mathrm{round}(3.75) \;=\; 4\,.$$

Table 2. Five regressions (one per column) for predicting $(\Delta pop)_t$.

	(1)	(2)	(3)	(4)	(5)
$temp_{t-1}$	0.816**	0.654			
	0.398	0.457			
$temp_{t-2}$		0.473			
		0.316			
$temp_{t-3}$		-0.134			
		0.367			
$temp_{t-4}$		-0.301			
		0.351			
$temp_{t-5}$		-0.0264			
		0.330			
$temp_{t-6}$		0.00773			
		0.307			
$\mathrm{MA}2_t$			1.143***		
			0.359		
$\mathrm{MA}5_t$				0.582	
				0.721	
$\mathrm{MA}10_t$					1.172
					0.971
$time$	-0.0208*	-0.0215*	-0.0216**	-0.0206*	-0.0175
	0.0108	0.0116	0.0108	0.0110	0.0118
$time^2$	0.000253**	0.000258**	0.000258**	0.000253**	0.000226**
	0.0000991	0.000108	0.000101	0.000102	0.000107
pop_t	-0.0879***	-0.0877***	-0.0885***	-0.0906***	-0.0862***
	0.0258	0.0276	0.0266	0.0252	0.0256
$(\Delta pop)_{t-1}$	0.392***	0.378***	0.367***	0.387***	0.383***
	0.0957	0.0984	0.0870	0.0999	0.104
constant	4.755***	4.765***	4.825***	4.874***	4.603***
	1.300	1.394	1.328	1.264	1.323

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1.

Consistent with the fact that there is little evidence of auto-correlation, robustness tests presented in the appendix show that the choice of error structure makes little difference to our overall conclusions.

5. Short-Term Temperature Effects

In table 2 we present our first set of regression results. In these regressions we estimate equation (3) using short run measures of climate. Our object is to understand the way that population growth rates respond to these short run changes.

In table 2 column 1 we consider only the previous year's temperature, $temp_{t-1}$ which is statistically significant ($p < 0.05$). However, combining the effects of the previous two years, by using $\mathrm{MA}2_t$ as in table 2 column 3 leads to an even more significant coefficient ($p < 0.01$) with value 1.143. This means that if the temperature increases by 1°C for one year, then in each of the two subsequent years the population growth rate will increase by 0.572%, for at total effect of 1.143%. If we instead use $\mathrm{MA}5_t$ or $\mathrm{MA}10_t$ as in table 2 columns (4) and (5), then the regression coefficients are not significantly different from zero. Taken together, regression results for $\mathrm{MA}2_t$, $\mathrm{MA}5_t$ and

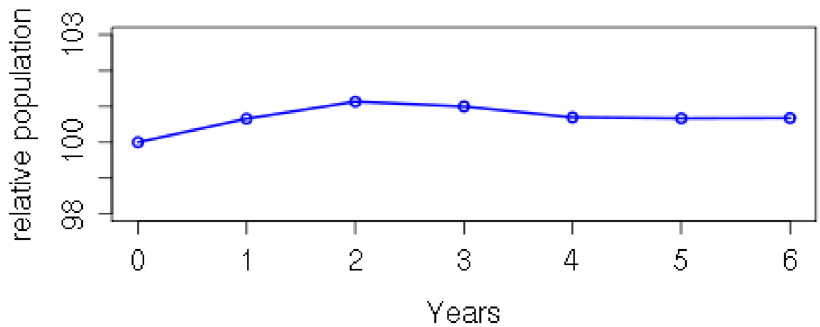


Figure 5. Predicted effect on total population of a temperature increase of one degree Celsius in year 0 only, assuming the growth rate is otherwise zero.

$\text{MA}10_t$ suggest that a one year warm shock drives up the population growth rate during the two years following the shock, after which the effect attenuates.

Table 2 column 2 shows a regression in which each of the previous six years' temperatures are treated as separate explanatory variables. An F-test rejects the hypothesis that they are jointly zero ($p < 0.02$), although none of the individual temperature variables is different from zero at standard levels of significance. To interpret these point estimates consider a one year temperature increase of 1°C in year 0. Figure 5 plots the resulting path of population. Consistent with the other results in table 2, figure 5 shows that, a one year temperature increase of 1°C causes a two year increase in the population growth rate which attenuates in the subsequent years.

From table 2 we also see that both *time* and $time^2$ are statistically significant, reflecting common trends not visible in figure 1. Interestingly, current population, pop_t, is also significant and negative. This confirms and quantifies our intuition that the population of Iceland is constrained by its resource base. Finally, the previous year's growth rate, $(\Delta pop)_{t-1}$, is significant and positive, reflecting latent factors which persist from year to year regardless of temperature.

In appendix table 4 we present variants of the regressions presented in column 1 of table 2. These complementary results demonstrate that our estimate of the effect of climate in column 1 of table 2 is robust to specification and estimation technique. In appendix tables 5-8 we present analogous estimates for columns 2 – 5 of table 2. These tables also confirm the robustness of our findings.

A. *Calculation of sustainable population levels*

While the discussion above is concerned with the effect of climate on the growth rate of population, our results also suggest a way to understand the effects of climate on Iceland's *steady state* population. To see this, suppose that temperature suddenly and persistently decreased by $\delta°$ C and the population growth rate,$(\Delta pop)_t$, remained constant. If nothing else changes then table 2 column 3 requires that population decrease so that $1.143\,\text{MA}2_t - 0.0885\,pop_t$ remains constant.

If we assume that the population is in equilibrium (i.e., that $(\Delta pop)_t \equiv 0$), or otherwise returns to the same value of $(\Delta pop)_t$, then table 2 column 3 implies that the quantity

$$1.143\,\textsc{ma}2_t - 0.0885\,pop_t$$

should be approximately constant. So, if the temperature suddenly and persistently decreased by δ degrees Celsius, and the society reverted to equilibrium at this new temperature, then we would have

$$\begin{aligned} 1.143\,prevtemp - 0.0885\,prevpop &= 1.143\,newtemp - 0.0885\,newpop \\ &= 1.143\,(prevtemp - \delta) - 0.0885\,newpop\,, \end{aligned}$$

from which it would follow that

$$newpop = 1 - \delta\frac{1.143}{0.0885} = prevpop - 12.91525\,\delta\,,$$

Since we are measuring population in thousands, this equation means that the resulting population decrease would be 12,915 times the decrease in temperature. So, if $\delta = 1$ (i.e. there is a one degree temperature decrease), then this would cause a drop of about 13,000 people, which for the population sizes we are considering in our data (i.e. around 50,000 people) represents about 26% of the population. Even if $\delta = 0.1$, then this would cause a drop of about 1,300 people, still a 2.6% decrease even from just a 0.1 degree Celsius sustained temperature drop.

The calculation above estimates long run changes in population on the basis of responses to short run variation in weather. Given that sustained changes in climate will likely induce more adaptive responses than will short run variation in weather, we are probably overstating the effects of climate on steady state population. With this in mind, we now investigate the effects of climate over a longer time horizon.

6. Long-Term Adaptation to Climate Change

We would like to understand the extent to which 18th and 19th century Icelanders adapt to persistent climate change. In particular, how effectively do 18th and 19th century Icelanders to adapt to climate change, and how long does this adaptation take?

A. *General adaptation*

A natural conjecture is that ten or twenty years of unusually harsh climate impoverishes the population and causes low growth or particular susceptibility to shocks in the years immediately following. Conversely, ten or twenty years of mild climate would have the opposite effect.

To test for this sort of generalized adaptation (really maladaptation) we investigate the effect of lagged long run moving averages of climate on current population growth rates. Table 3 columns 1 – 3 indicates that there is no statistically significant effect of long-term climate histories such as $\textsc{ma}20_{t-4}$ (nor $\textsc{ma}10_{t-4}$ nor $\textsc{ma}50_{t-4}$). Furthermore, table 3 columns 4 – 6 indicate that this non-effect persists even once short-term temperatures (from $\textsc{ma}2_t$) are separately taken into account.

Table 3. Nine regressions (one per column) for predicting $(\Delta pop)_t$.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$\text{MA}2_t$				1.153***	1.133***	1.231***	1.084***	1.104***	1.218***
				0.355	0.353	0.350	0.323	0.298	0.356
$\text{MA}10_{t-4}$	0.364			0.485			0.710		
	1.051			1.017			1.044		
$\text{MA}20_{t-4}$		-0.897			-0.208			-0.00492	
		1.590			1.572			1.544	
$\text{MA}50_{t-4}$			-1.127			3.465			3.259
			5.186			5.356			5.272
$\text{MA}2_t \times \text{MA}10_{t-4}$							7.690*		
							4.454		
$\text{MA}2_t \times \text{MA}20_{t-4}$								11.10*	
								5.906	
$\text{MA}2_t \times \text{MA}50_{t-4}$									5.372
									14.20
time	-0.0190	-0.0239*	-0.0211*	-0.0195	-0.0224*	-0.0202*	-0.0230*	-0.0272**	-0.0213*
	0.0121	0.0128	0.0120	0.0119	0.0129	0.0111	0.0123	0.0133	0.0118
$time^2$	0.000243**	0.000280**	0.000252**	0.000241**	0.000264**	0.000271***	0.000267**	0.000302**	0.000281**
	0.000109	0.000112	0.000103	0.000108	0.000114	0.000102	0.000110	0.000117	0.000109
pop_t	-0.0900***	-0.0929***	-0.0894***	-0.0866***	-0.0889***	-0.0945***	-0.0917***	-0.0926***	-0.0965***
	0.0249	0.0256	0.0268	0.0262	0.0272	0.0289	0.0264	0.0277	0.0302
$(\Delta pop)_{t-1}$	0.394***	0.393***	0.394***	0.364***	0.367***	0.370***	0.359***	0.358***	0.365***
	0.107	0.103	0.102	0.0881	0.0867	0.0883	0.0921	0.0891	0.0932
constant	4.781***	5.052***	4.843***	4.687***	4.864***	4.946***	5.033***	5.182***	5.075***
	1.293	1.329	1.290	1.341	1.397	1.343	1.371	1.439	1.438

Standard errors in parentheses. P-values: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

The results in columns 1 – 6 of table 3 indicate that this sort of generalized adaptation, if it occurs at all, has too small an effect to be measured in our sample.

In appendix table 9 we present variants of the regressions presented in column 1 of table 3. These complementary results demonstrate that our estimate of the effect of climate in column 1 of table 3 is robust to specification and estimation technique. In appendix tables 10-14 we present analogous estimates for columns 2 – 6 of table 3. These tables also confirm the robustness of the results presented in table 3.

B. *Specific adaptation*

The preceding section asks whether prolonged climate change leads to generalized adaptations that affect the population growth rate. We now ask whether long-term climate changes lead to specific adaptations which affect the way the population responds to short term climate shocks. That is, we would like to know whether the effect of a cold year is different if it follows a period of harsh climate than if it follows a period of mild climate.

To investigate the possibility that the effect of a short run climate shock depends on the long run climate history that precedes it, table 3 columns (7)–(9) include not only short-term temperature shocks such as $\text{MA}2_t$ and long-term climate changes such as $\text{MA}20_{t-4}$, but also *interactions* between these two effects such as $\text{MA}2_t \times \text{MA}20_{t-4}$. These interaction variables allow us to investigate whether, for example, short-term temperature decreases have a larger negative effect during warm-climate periods (when the population is not well adapted to cold) than during cold-climate periods (when the population has already adapted to the cold).

We note that this sort of specific adaptation is broadly consistent with the archeological record. In particular, archeological evidence suggests that during cold periods Icelanders live in smaller houses, live closer to their animals, and are smaller Karlsson (2000). Each of these adaptations plausibly improves fitness under cold conditions and would probably occur over the course of a generation.

Table 3 provides evidence of specific adaptation to climate. Table 3 column 7 shows that the interaction variable $\text{MA2}_t \times \text{MA10}_{t-4}$ has a somewhat significant ($p < 0.1$) positive regression coefficient of 7.690. Table 3 column 8 shows that the interaction variable $\text{MA2}_t \times \text{MA20}_{t-4}$ has slightly larger coefficient of 11.10 with about the same level of significance. Table 3 column 9 shows that the interaction variable $\text{MA2}_t \times \text{MA50}_{t-4}$, while positive, is smaller than the ten and twenty year interaction terms and is not distinguishable from zero. This suggests that long run adaptation to climate change does occur, that this adaptation is underway way after ten years and continues for at least another ten years.

In appendix table 15 we present variants of the regressions presented in column 7 of table 3. These complementary results demonstrate that our estimate of the effect of climate in column 1 of table 3 is robust to specification and estimation technique. In appendix tables 16 and 17 we present analogous estimates for columns 8 and 9 of table 3. These tables also confirm the robustness of the results presented in table 3.

C. *Magnitude of interaction effects*

We now consider the magnitude of the effects of the interaction terms, i.e. the extent to which the effects of short-term temperature shock are modified due to long-term climate change. To investigate this, we imagine that we begin with the climate equal to its overall mean values during our study years, so that the "demeaned" variables MA2 and MA20 both start equal to zero.

Suppose first that the short term temperature, MA2, suddenly increases by δ degrees. Then according to table 3 column 8, Δpop would correspondingly increase by the short-term shock amount

$$ST(\delta) \;=\; 1.104\,\delta\,.$$

If instead the overall climate *persistently* increased by ϵ degrees, so that both MA2 and MA20 each increased by ϵ, then Δpop would correspondingly increase by the long-term climate-change amount

$$LT(\epsilon) \;=\; 1.104\,\epsilon - 0.00492\,\epsilon + 11.10\,\epsilon^2 \;=\; 1.09908\,\epsilon + 11.10\,\epsilon^2\,.$$

Now suppose that these two effects *both* happened, i.e. that MA20 increased by ϵ while MA2 increased by $\delta + \epsilon$. Then Δpop would correspondingly increase by the short-long combined amount

$$SLT(\delta,\epsilon) \;=\; 1.104\,(\delta+\epsilon) - 0.00492\,\epsilon + 11.10\,\epsilon(\delta+\epsilon)\,.$$

In this scenario, the amount of this increase in Δpop which was due to the short-term temperature shock would be $SLT(\delta,\epsilon) - LT(\epsilon)$.

Hence, in this scenario, the *fraction* by which the effect of a short-term temperature shock has been multiplied due to the long-term climate change can be measured by

$$Ratio(\delta,\epsilon) \ := \ \frac{SLT(\delta,\epsilon) - LT(\epsilon)}{ST(\delta)} \, ,$$

which simplifies to

$$Ratio(\delta,\epsilon) \ = \ 1 + 10.0543\,\epsilon \, , \tag{4}$$

and in fact turns out not to depend on δ.

Thus, for long run climate change ϵ in the range $\pm 0.1^\circ$ C this ratio varies from about 0 to nearly 2. That is, long-run climate changes could do anything from completely remove the short-term temperature shock effects (for climates about 0.1 degrees colder), to nearly double them (for climates about 0.1 degrees warmer).

In fact the standard deviation of the observed values of $\text{MA}20_t$ in our sample is only about 0.06 degrees Celsius. This is the empirical variation on which the estimates are based and thus is a reasonable value to use to evaluate the magnitude of the estimated interaction effect. For this small value of δ, we find that $Ratio(\delta,0.06) = 1.603258$. That is, the effect of short-term temperature shocks increases by about 60% if climate persistently warms by just 0.06° C. On the other hand, if the climate persistently cools by 0.06° C, $Ratio(\delta,-0.06) = 0.396742$, so that the effect of short-term temperature shocks decreases by about 60%.[6]

In light of the evidence for adaptation, it probably makes sense to revise the estimate of the effect of climate on steady state population from section 5A. The estimates in Table 2 do not allow for long run adaptation to climate. On the basis of Table 3 column 8 and the discussion above, we should expect such adaptation to reduce the effects of climate on population by about 60%. This suggests that we expect a long run δ° C temperature decrease to lead to a decrease in steady state population on the order of $(1 - 0.6) \times 26\%$ or about 10%.

7. Conclusion

We investigate the effect of climate on population levels in pre-industrial Iceland. We find that short-term temperature changes significantly affect the population growth rate. In particular, a 1° C decrease in temperature causes about 0.57% decrease in the population growth rate for the two subsequent years, for a total effect of 1.14%. This effect appears to attenuate as the growth rate returns to trend in subsequent years. We also quantify the extent to which 18th and 19th century Icelanders adapt to long run climate change. In particular, the data suggest that long run adaptation to climate takes about 20 years and reduces the effect of cold shocks by about 60%. Our results also allow us to approximate the effect of permanent climate change on steady state population levels. This approximation suggests that steady state population levels decrease by 10% to 26% for each 1° C of sustained adverse temperature change.

[6]The standard deviation of the observed values of $\text{MA}2_t$ in our sample is about 0.19 degrees Celsius. However, (4) does not depend on δ.

Using data on Iceland's historical GDP from Jonsson (Amsterdam, 2004) (see Norges Handelshoyskole (2010)), and current and historical GDP from the Penn World Tables (Heston, Summers, and Aten, 2010), we estimate that Iceland's per capita GDP in 1870 was about $1436 in 2005 US dollars. Again using the Penn World Tables (Heston *et al.*, 2010), we find that 23 of the 190 countries covered in this data had per capita GDPs at or below this level in 2005. These countries account for about 5% of the population covered by the Penn world table in 2005, nearly 400 million people.

We currently have little basis for anticipating the effects that global warming will have on these populations. However, if contemporary poor agricultural populations behave like their 18th and 19th century Icelandic counterparts, then our results inform us about the rate and extent to which they will adapt to global warming. In particular, our results suggest that adverse climate change (which now refers to warming, not cooling) will have three effects on poor contemporary populations. First, in the short run it will lead to a significant decrease in population growth rates. Second, over the course of a generation, adaptation will offset about 60% of the short-run effects. Finally, in the long run, we expect a 10-26% decrease in steady state populations.

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Appendix A. Appendix: Robustness tests for Tables 2 and 3

We now present various robustness tests for the regression results in tables 2 and 3. Each table below corresponds to a single column of table 2 or 3. In each case, the column marked with an asterisk repeats the result from table 2 or 3, while the remaining columns vary technical details such as: how temperature is estimated; estimation technique; which lagged Δpop variables are included, and end year of the study period.

While the results are not identical in the different columns, usually they are fairly similar and thus show that our broad conclusions are not sensitive to these various design choices.

Below, $temp_t$ is our usual estimated temperature of Iceland based on the best-fit linear function of the Crete ice core delta, $Milcent_t$ is the estimated temperature based on the best-fit linear function of the Millicent ice core delta, and $qCrete_t$ is the estimated temperature based on the best-fit *quadratic* function of the Crete ice core delta. For the moving averages, we use abbreviations such as MA2(Mil) for those based on a linear function of the Millicent ice core delta, and MA2(qCr) for those based on a quadratic function of the Crete ice core delta. Our start-year is always 1735, while our end-year is usually 1860 but is occasionally 1820 or 1860, as indicated.

Table 4. Robustness tests for table 2 column 1.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$temp_{t-1}$	0.865*	0.544*	0.897*	0.914*	0.590	0.816**	0.772**	0.766*		
	0.521	0.323	0.506	0.540	0.463	0.398	0.389	0.392		
$Milcent_{t-1}$									1.092***	
									0.339	
$qCrete_{t-1}$										0.616
										0.532
$time$	-0.0209*	-0.0257		0.0108	-0.0118	-0.0208*	-0.0165	-0.0201*	-0.0180	-0.0211
	0.0126	0.0175		0.0161	0.00954	0.0108	0.0105	0.0119	0.0119	0.0131
$time^2$	0.000254**	0.000332*		-0.000151	0.000171*	0.000253**	0.000206**	0.000243**	0.000237**	0.000257**
	0.000117	0.000168		0.000164	0.0000889	0.0000991	0.0000976	0.000110	0.000106	0.000119
pop_t	-0.0787**	-0.118**		-0.113**	-0.0759**	-0.0879***	-0.0715***	-0.0840***	-0.0797***	-0.0789**
	0.0333	0.0466		0.0482	0.0322	0.0258	0.0272	0.0300	0.0281	0.0331
$(\Delta pop)_{t-1}$						0.392***	0.479***	0.508***		
						0.0957	0.133	0.132		
$(\Delta pop)_{t-2}$							-0.0999*	-0.159***		
							0.0564	0.0508		
$(\Delta pop)_{t-3}$								0.0748		
								0.0529		
constant	4.535***	6.367***	0.664***	5.709**	4.244***	4.755***	3.897***	4.538***	4.478***	4.540***
	1.597	2.303	0.116	2.167	1.535	1.300	1.371	1.538	1.354	1.588
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 5. Robustness tests for table 2 column 2.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$temp_{t-1}$	0.666	0.655**	0.701	0.775*	0.443	0.654	0.639	0.619	0.973***	0.364
	0.528	0.329	0.524	0.450	0.451	0.457	0.451	0.468	0.344	0.546
$temp_{t-2}$	0.629**	0.638*	0.657***	0.183	0.514**	0.473	0.429	0.455	0.657**	0.675**
	0.248	0.324	0.248	0.323	0.235	0.316	0.357	0.411	0.321	0.282
$temp_{t-3}$	0.212	0.219	0.198	0.0754	0.351	-0.134	-0.132	-0.0939	0.323	-0.125
	0.384	0.335	0.407	0.396	0.326	0.367	0.386	0.392	0.342	0.381
$temp_{t-4}$	-0.404	-0.438	-0.366	-0.499	-0.546*	-0.301	-0.300	-0.339	0.462	-0.519
	0.357	0.324	0.352	0.354	0.320	0.351	0.340	0.351	0.467	0.425
$temp_{t-5}$	-0.119	-0.170	-0.0576	-0.107	-0.0570	-0.0264	-0.0322	-0.0343	-0.00916	-0.130
	0.331	0.322	0.317	0.407	0.285	0.330	0.318	0.303	0.495	0.344
$temp_{t-6}$	-0.109	-0.342	-0.0177	-0.183	-0.111	0.00773	-0.0424	-0.0368	-0.0208	-0.102
	0.321	0.318	0.298	0.260	0.283	0.307	0.306	0.314	0.450	0.323
$time$	-0.0226	-0.0304*		0.0124	-0.0127	-0.0215*	-0.0169	-0.0194	-0.0167	-0.0231
	0.0139	0.0180		0.0182	0.0106	0.0116	0.0113	0.0130	0.0112	0.0145
$time^2$	0.000269**	0.000376**		-0.000172	0.000179*	0.000258**	0.000211**	0.000241**	0.000234**	0.000278**
	0.000131	0.000173		0.000184	0.000101	0.000108	0.000106	0.000120	0.0000990	0.000137
pop_t	-0.0813**	-0.127***		-0.124**	-0.0778**	-0.0877***	-0.0721**	-0.0842***	-0.0859***	-0.0829**
	0.0363	0.0476		0.0519	0.0357	0.0276	0.0288	0.0318	0.0285	0.0380
$(\Delta pop)_{t-1}$						0.378***	0.455***	0.484***		
						0.0984	0.137	0.140		
$(\Delta pop)_{t-2}$							-0.0885	-0.157***		
							0.0564	0.0525		
$(\Delta pop)_{t-3}$								0.0874		
								0.0614		
constant	4.692***	6.878***	0.668***	6.200**	4.359**	4.765***	3.933***	4.527***	4.699***	4.759**
	1.770	2.356	0.119	2.375	1.723	1.394	1.452	1.633	1.331	1.851
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.
In columns 1 – 7, temperature measures are based on linear Crete imputation.
In column 8, temperature measures are based on Millicent imputation.
In column 9, temperature measures are based on quadratic Crete imputation.

Table 6. Robustness tests for table 2 column 3.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$\mathrm{MA}2_t$	1.383**	1.303***	1.426**	1.158*	1.053**	1.143***	1.072***	1.082***		
	0.562	0.461	0.546	0.658	0.507	0.359	0.358	0.360		
$\mathrm{MA}2(Mil)_t$									1.643***	
									0.500	
$\mathrm{MA}2(qCr)_t$										1.035*
										0.532
$time$	-0.0209*	-0.0256		0.00935	-0.0113	-0.0216**	-0.0174*	-0.0200*	-0.0175	-0.0213*
	0.0121	0.0170		0.0164	0.00946	0.0108	0.0104	0.0120	0.0114	0.0129
$time^2$	0.000252**	0.000325**		-0.000134	0.000164*	0.000258**	0.000214**	0.000243**	0.000235**	0.000256**
	0.000114	0.000163		0.000167	0.0000893	0.000101	0.0000967	0.000110	0.000102	0.000118
pop_t	-0.0780**	-0.114**		-0.110**	-0.0732**	-0.0885***	-0.0731***	-0.0850***	-0.0821***	-0.0778**
	0.0333	0.0454		0.0490	0.0324	0.0266	0.0272	0.0297	0.0278	0.0332
$(\Delta pop)_{t-1}$						0.367***	0.450***	0.481***		
						0.0870	0.124	0.125		
$(\Delta pop)_{t-2}$							-0.0930*	-0.160***		
							0.0556	0.0517		
$(\Delta pop)_{t-3}$								0.0853		
								0.0571		
constant	4.515***	6.204***	0.668***	5.624**	4.122***	4.825***	4.011***	4.598***	4.564***	4.511***
	1.598	2.243	0.116	2.191	1.545	1.328	1.354	1.516	1.335	1.592
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 7. Robustness tests for table 2 column 4.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$\mathrm{MA}5_t$	0.897	0.974	1.041	0.0695	0.608	0.582	0.520	0.520		
	0.874	0.915	0.860	0.740	0.699	0.721	0.682	0.680		
$\mathrm{MA}5(Mil)_t$									2.459***	
									0.875	
$\mathrm{MA}5(qCr)_t$										0.160
										0.888
$time$	-0.0192	-0.0243		0.0186	-0.0112	-0.0206*	-0.0174	-0.0207*	-0.0176	-0.0199
	0.0125	0.0181		0.0144	0.00964	0.0110	0.0105	0.0119	0.0114	0.0131
$time^2$	0.000242**	0.000324*		-0.000238	0.000167*	0.000253**	0.000215**	0.000250**	0.000250**	0.000251**
	0.000117	0.000174		0.000156	0.0000899	0.000102	0.0000971	0.000109	0.000107	0.000121
pop_t	-0.0792**	-0.122**		-0.124***	-0.0757**	-0.0906***	-0.0741***	-0.0867***	-0.0933***	-0.0805**
	0.0317	0.0481		0.0456	0.0317	0.0252	0.0261	0.0287	0.0315	0.0329
$(\Delta pop)_{t-1}$						0.387***	0.489***	0.520***		
						0.0999	0.145	0.146		
$(\Delta pop)_{t-2}$							-0.118**	-0.181***		
							0.0590	0.0552		
$(\Delta pop)_{t-3}$								0.0802		
								0.0522		
constant	4.519***	6.495***	0.664***	6.098***	4.215***	4.874***	4.041***	4.676***	5.042***	4.574***
	1.523	2.378	0.118	2.058	1.512	1.264	1.304	1.464	1.483	1.585
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 8. Robustness tests for table 2 column 5.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$\text{MA}10_t$	1.649	2.143	2.081	1.919*	1.298	1.172	1.193	1.332		
	1.296	1.560	1.276	1.024	1.028	0.971	0.960	0.962		
$\text{MA}10(Mil)_t$									3.603*	
									2.029	
$\text{MA}10(qCr)_t$										0.460
										1.072
$time$	-0.0145	-0.0174		0.0165	-0.00887	-0.0175	-0.0147	-0.0185	-0.0141	-0.0183
	0.0135	0.0190		0.0145	0.0102	0.0118	0.0113	0.0124	0.0149	0.0140
$time^2$	0.000200	0.000261		-0.000206	0.000147	0.000226**	0.000190*	0.000229**	0.000240*	0.000235*
	0.000123	0.000182		0.000154	0.0000919	0.000107	0.000101	0.000110	0.000124	0.000130
pop_t	-0.0724**	-0.112**		-0.101**	-0.0697**	-0.0862***	-0.0699***	-0.0832***	-0.105***	-0.0775**
	0.0312	0.0489		0.0435	0.0317	0.0256	0.0261	0.0284	0.0365	0.0339
$(\Delta pop)_{t-1}$						0.383***	0.486***	0.516***		
						0.104	0.146	0.146		
$(\Delta pop)_{t-2}$							-0.121**	-0.184***		
							0.0580	0.0547		
$(\Delta pop)_{t-3}$								0.0806		
								0.0514		
constant	4.098***	5.898**	0.653***	5.033**	3.881**	4.603***	3.793***	4.478***	5.425***	4.402***
	1.551	2.435	0.117	1.987	1.543	1.323	1.343	1.482	1.693	1.668
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 9. Robustness tests for table 3 column 1.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$\text{MA}10_{t-4}$	0.629	0.912	0.874	1.069	0.946	0.364	0.496	0.490		
	1.507	1.534	1.363	1.477	1.173	1.051	1.050	1.041		
$\text{MA}10(Mil)_{t-4}$									-1.556	
									2.069	
$\text{MA}10(qC)_{t-4}$										0.220
										1.233
$time$	-0.0171	-0.0214		0.0223	-0.00980	-0.0190	-0.0151	-0.0187	-0.0234	-0.0188
	0.0155	0.0197		0.0161	0.0106	0.0121	0.0118	0.0128	0.0141	0.0152
$time^2$	0.000229*	0.000306		-0.000273*	0.000162*	0.000243**	0.000199*	0.000236**	0.000260**	0.000242*
	0.000136	0.000186		0.000164	0.0000906	0.000109	0.000105	0.000114	0.000124	0.000135
pop_t	-0.0787**	-0.123**		-0.118***	-0.0757**	-0.0900***	-0.0724***	-0.0851***	-0.0706**	-0.0798**
	0.0309	0.0491		0.0413	0.0298	0.0249	0.0255	0.0283	0.0334	0.0317
$(\Delta pop)_{t-1}$						0.394***	0.499***	0.529***		
						0.107	0.152	0.152		
$(\Delta pop)_{t-2}$							-0.123**	-0.184***		
							0.0581	0.0554		
$(\Delta pop)_{t-3}$								0.0779		
								0.0493		
constant	4.416***	6.438***	0.648***	5.736***	4.145***	4.781***	3.885***	4.534***	4.266***	4.508***
	1.540	2.454	0.119	1.902	1.459	1.293	1.320	1.488	1.553	1.568
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 10. Robustness tests for table 3 column 2.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$\text{MA}20_{t-4}$	-1.386	-2.288	-0.759	0.839	-0.322	-0.897	-0.787	-0.720		
	2.334	2.496	1.705	2.566	1.947	1.590	1.531	1.552		
$\text{MA}20(Mil)_{t-4}$									-5.574	
									4.483	
$\text{MA}20(qCr)_{t-4}$										-1.781
										1.869
$time$	-0.0254	-0.0352*		0.0232	-0.0127	-0.0239*	-0.0200*	-0.0229*	-0.0264*	-0.0278*
	0.0170	0.0211		0.0222	0.0111	0.0128	0.0119	0.0129	0.0136	0.0160
$time^2$	0.000291**	0.000412**		-0.000283	0.000181*	0.000280**	0.000236**	0.000267**	0.000243**	0.000312**
	0.000144	0.000191		0.000218	0.0000937	0.000112	0.000105	0.000115	0.000118	0.000140
pop_t	-0.0840**	-0.133***		-0.124***	-0.0793**	-0.0929***	-0.0755***	-0.0877***	-0.0559	-0.0875***
	0.0329	0.0492		0.0450	0.0313	0.0256	0.0266	0.0294	0.0344	0.0327
$(\Delta pop)_{t-1}$						0.393***	0.496***	0.527***		
						0.103	0.147	0.148		
$(\Delta pop)_{t-2}$							-0.119**	-0.182***		
							0.0568	0.0546		
$(\Delta pop)_{t-3}$								0.0803		
								0.0498		
constant	4.883***	7.270***	0.661***	6.006***	4.406***	5.052***	4.161***	4.766***	3.836**	5.107***
	1.640	2.476	0.119	2.066	1.521	1.329	1.350	1.518	1.533	1.619
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 11. Robustness tests for table 3 column 3.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$\text{MA}50_{t-4}$	-3.245	2.408	-3.702	3.565	-4.479	-1.127	-0.573	-1.126		
	7.461	7.549	3.516	5.664	6.704	5.186	4.849	4.750		
$\text{MA}50(Mil)_{t-4}$									1.600	
									6.566	
$\text{MA}50(qCr)_{t-4}$										-3.671
										6.592
$time$	-0.0213	-0.0248		0.0228	-0.0154	-0.0211*	-0.0175	-0.0210	-0.0237	-0.0217
	0.0144	0.0190		0.0139	0.0121	0.0120	0.0116	0.0130	0.0205	0.0142
$time^2$	0.000240**	0.000353*		-0.000260*	0.000176*	0.000252**	0.000214**	0.000247**	0.000293	0.000243**
	0.000120	0.000179		0.000147	0.0000909	0.000103	0.000101	0.000113	0.000200	0.000121
pop_t	-0.0753**	-0.133**		-0.134***	-0.0728**	-0.0894***	-0.0733**	-0.0850***	-0.0893**	-0.0742**
	0.0360	0.0509		0.0407	0.0340	0.0268	0.0280	0.0304	0.0397	0.0348
$(\Delta pop)_{t-1}$						0.394***	0.499***	0.528***		
						0.102	0.147	0.148		
$(\Delta pop)_{t-2}$							-0.120**	-0.184***		
							0.0580	0.0550		
$(\Delta pop)_{t-3}$								0.0815		
								0.0511		
constant	4.476***	6.884***	0.668***	6.390***	4.309***	4.843***	4.005***	4.625***	5.017**	4.434***
	1.616	2.448	0.120	1.834	1.553	1.290	1.355	1.525	2.005	1.598
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 12. Robustness tests for table 3 column 4.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$\textsc{ma}2_t$	1.395**	1.304***	1.452***	1.292**	1.093**	1.153***	1.076***	1.082***		
	0.558	0.462	0.539	0.622	0.507	0.355	0.357	0.361		
$\textsc{ma}10_{t-4}$	0.749	0.885	1.041	1.650	1.126	0.485	0.539	0.496		
	1.463	1.439	1.330	1.527	1.107	1.017	1.033	1.019		
$\textsc{ma}2(Mil)_t$									1.615***	
									0.514	
$\textsc{ma}10(Mil)_{t-4}$									-0.336	
									2.009	
$\textsc{ma}2(qCr)_t$										1.047**
										0.522
$\textsc{ma}10(qCr)_{t-4}$										0.366
										1.220
time	-0.0175	-0.0213		0.0134	-0.00873	-0.0195	-0.0151	-0.0181	-0.0183	-0.0194
	0.0147	0.0183		0.0178	0.0103	0.0119	0.0115	0.0125	0.0130	0.0151
$time^2$	0.000224*	0.000289*		-0.000169	0.000145	0.000241**	0.000195*	0.000228**	0.000237**	0.000240*
	0.000130	0.000173		0.000174	0.0000899	0.000108	0.000103	0.000113	0.000106	0.000134
pop_t	-0.0751**	-0.110**		-0.0982**	-0.0688**	-0.0866***	-0.0710***	-0.0832***	-0.0798***	-0.0755**
	0.0318	0.0458		0.0423	0.0305	0.0262	0.0263	0.0289	0.0293	0.0324
$(\Delta pop)_{t-1}$						0.364***	0.449***	0.479***		
						0.0881	0.126	0.126		
$(\Delta pop)_{t-2}$							-0.0954*	-0.161***		
							0.0558	0.0523		
$(\Delta pop)_{t-3}$								0.0832		
								0.0567		
constant	4.297***	5.907**	0.659***	4.953**	3.838**	4.687***	3.860***	4.471***	4.493***	4.359***
	1.571	2.287	0.117	1.925	1.488	1.341	1.340	1.496	1.347	1.596
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 13. Robustness tests for table 3 column 5.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$\text{MA}2_t$	1.358**	1.268***	1.428***	1.221*	1.100**	1.133***	1.062***	1.074***		
	0.533	0.466	0.528	0.632	0.502	0.353	0.352	0.356		
$\text{MA}20_{t-4}$	-0.539	-1.414	0.0288	1.775	0.614	-0.208	-0.237	-0.203		
	2.180	2.360	1.721	2.348	1.839	1.572	1.512	1.528		
$\text{MA}2(Mil)_t$									1.539***	
									0.551	
$\text{MA}20(Mil)_{t-4}$									-3.154	
									4.693	
$\text{MA}2(qCr)_t$										0.967*
										0.517
$\text{MA}20(qCr)_{t-4}$										-1.157
										1.851
time	-0.0230	-0.0314		0.0176	-0.0100	-0.0224*	-0.0182	-0.0207	-0.0213*	-0.0263*
	0.0159	0.0197		0.0240	0.0107	0.0129	0.0117	0.0128	0.0126	0.0158
$time^2$	0.000267*	0.000369**		-0.000214	0.000157*	0.000264**	0.000220**	0.000248**	0.000231**	0.000295**
	0.000138	0.000179		0.000236	0.0000939	0.000114	0.000104	0.000114	0.000103	0.000140
pop_t	-0.0791**	-0.119**		-0.108**	-0.0728**	-0.0889***	-0.0734***	-0.0853***	-0.0678**	-0.0822**
	0.0340	0.0462		0.0482	0.0324	0.0272	0.0273	0.0298	0.0332	0.0340
$(\Delta pop)_{t-1}$						0.367***	0.449***	0.480***		
						0.0867	0.123	0.125		
$(\Delta pop)_{t-2}$							-0.0928*	-0.160***		
							0.0549	0.0517		
$(\Delta pop)_{t-3}$								0.0853		
								0.0571		
constant	4.627***	6.561***	0.668***	5.330**	4.055**	4.864***	4.052***	4.629***	4.135***	4.847***
	1.676	2.326	0.119	2.146	1.574	1.397	1.363	1.513	1.417	1.677
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1

Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 14. Robustness tests for table 3 column 6.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)	(9)	(10)
$\text{MA}2_t$	1.443***	1.358***	1.366**	1.276*	1.024**	1.231***	1.164***	1.155***		
	0.518	0.469	0.531	0.662	0.477	0.350	0.351	0.361		
$\text{MA}50_{t-4}$	2.303	5.289	-1.630	6.692	-1.481	3.465	3.581	2.915		
	7.109	7.220	3.793	5.803	6.380	5.356	5.087	5.023		
$\text{MA}2(Mil)_t$									1.650***	
									0.487	
$\text{MA}50(Mil)_{t-4}$									2.128	
									6.396	
$\text{MA}2(qCr)_t$										1.032**
										0.515
$\text{MA}50(qCr)_{t-4}$										-0.106
										6.671
$time$	-0.0200	-0.0232		0.0154	-0.0125	-0.0202*	-0.0158	-0.0188	-0.0224	-0.0214
	0.0128	0.0176		0.0156	0.0110	0.0111	0.0107	0.0121	0.0186	0.0136
$time^2$	0.000261**	0.000345**		-0.000157	0.000163*	0.000271***	0.000227**	0.000254**	0.000289	0.000256**
	0.000113	0.000167		0.000162	0.0000904	0.000102	0.0000980	0.000111	0.000183	0.000118
pop_t	-0.0820**	-0.124**		-0.127***	-0.0712**	-0.0945***	-0.0791***	-0.0897***	-0.0929**	-0.0776**
	0.0358	0.0475		0.0424	0.0343	0.0289	0.0292	0.0319	0.0369	0.0350
$(\Delta pop)_{t-1}$						0.370***	0.453***	0.482***		
						0.0883	0.126	0.127		
$(\Delta pop)_{t-2}$							-0.0932*	-0.158***		
							0.0537	0.0523		
$(\Delta pop)_{t-3}$								0.0817		
								0.0548		
constant	4.598***	6.425***	0.673***	6.057***	4.107**	4.946***	4.129***	4.684***	5.120***	4.507***
	1.601	2.281	0.120	1.906	1.575	1.343	1.365	1.537	1.860	1.606
end-year	1860	1860	1860	1820	1880	1860	1860	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 15. Robustness tests for table 3 column 7.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)
$\text{MA}2_t$	1.316**	1.123**	1.374***	1.103*	1.086**	1.084***	1.026***	1.044***
	0.521	0.476	0.513	0.588	0.448	0.323	0.313	0.318
$\text{MA}10_{t-4}$	0.982	1.048	1.339	1.910	1.282	0.710	0.772	0.688
	1.483	1.430	1.366	1.503	1.044	1.044	1.044	1.026
$\text{MA}2_t \times \text{MA}10_{t-4}$	8.267	7.763	7.129	6.857	9.828**	7.690*	9.582**	9.086**
	6.052	5.229	5.602	5.357	4.868	4.454	4.316	4.423
$time$	-0.0207	-0.0239		0.0123	-0.0139	-0.0230*	-0.0178	-0.0197
	0.0151	0.0182		0.0181	0.0113	0.0123	0.0112	0.0121
$time^2$	0.000247*	0.000307*		-0.000167	0.000183*	0.000267**	0.000212**	0.000236**
	0.000131	0.000171		0.000176	0.0000947	0.000110	0.0000995	0.000109
pop_t	-0.0798**	-0.113**		-0.106**	-0.0744**	-0.0917***	-0.0740***	-0.0841***
	0.0314	0.0454		0.0414	0.0298	0.0264	0.0258	0.0284
$(\Delta pop)_{t-1}$						0.359***	0.443***	0.471***
						0.0921	0.129	0.130
$(\Delta pop)_{t-2}$							-0.0974*	-0.158***
							0.0545	0.0533
$(\Delta pop)_{t-3}$								0.0769
								0.0567
constant	4.619***	6.141***	0.662***	5.350***	4.249***	5.033***	4.098***	4.581***
	1.571	2.271	0.115	1.900	1.465	1.371	1.305	1.461
end-year	1860	1860	1860	1820	1880	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 16. Robustness tests for table 3 column 8.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)
MA2_t	1.317***	1.168**	1.400***	0.950*	1.085**	1.104***	1.091***	1.116***
	0.444	0.479	0.446	0.560	0.425	0.298	0.294	0.299
MA20_{t-4}	-0.337	-1.310	0.489	2.237	1.017	-0.00492	-0.0984	-0.125
	2.157	2.307	1.904	2.145	1.870	1.544	1.490	1.495
MA2_t $\times$ MA20_{t-4}	12.28	6.491	10.33	10.92	11.94	11.10*	13.35**	13.77**
	8.110	7.037	8.485	10.04	7.611	5.906	5.695	5.939
$time$	-0.0277*	-0.0331*		0.0163	-0.0138	-0.0272**	-0.0222*	-0.0240*
	0.0163	0.0194		0.0239	0.0110	0.0133	0.0116	0.0127
$time^2$	0.000303**	0.000379**		-0.000209	0.000186*	0.000302**	0.000251**	0.000272**
	0.000141	0.000176		0.000234	0.0000961	0.000117	0.000103	0.000113
pop_t	-0.0824**	-0.116**		-0.115**	-0.0748**	-0.0926***	-0.0758***	-0.0865***
	0.0343	0.0451		0.0485	0.0321	0.0277	0.0272	0.0296
$(\Delta pop)_{t-1}$						0.358***	0.425***	0.454***
						0.0891	0.126	0.127
$(\Delta pop)_{t-2}$							-0.0784	-0.148***
							0.0532	0.0502
$(\Delta pop)_{t-3}$								0.0889
								0.0566
constant	4.921***	6.525***	0.688***	5.696**	4.263***	5.182***	4.296***	4.798***
	1.709	2.274	0.112	2.185	1.556	1.439	1.358	1.510
end-year	1860	1860	1860	1820	1880	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.

Table 17. Robustness tests for table 3 column 9.

	(1)	(2)	(3)	(4)	(5)	(6*)	(7)	(8)
MA2_t	1.400***	1.323***	1.350**	0.894	1.071**	1.218***	1.134***	1.140***
	0.505	0.480	0.532	1.230	0.425	0.356	0.355	0.363
MA50_{t-4}	1.800	5.086	-1.702	6.657	-1.827	3.259	3.147	2.720
	6.958	7.232	3.743	5.681	6.087	5.272	4.854	4.922
MA2_t $\times$ MA50_{t-4}	14.53	6.541	6.502	18.29	21.39	5.372	11.97	6.773
	17.44	16.74	19.00	33.76	14.07	14.20	12.63	14.08
$time$	-0.0226*	-0.0242		0.0158	-0.0156	-0.0213*	-0.0176	-0.0194
	0.0136	0.0178		0.0159	0.0116	0.0118	0.0110	0.0123
$time^2$	0.000284**	0.000353**		-0.000164	0.000193**	0.000281**	0.000241**	0.000259**
	0.000121	0.000169		0.000166	0.0000950	0.000109	0.000103	0.000113
pop_t	-0.0872**	-0.126***		-0.140***	-0.0804**	-0.0965***	-0.0814***	-0.0899***
	0.0367	0.0479		0.0479	0.0343	0.0302	0.0297	0.0320
$(\Delta pop)_{t-1}$						0.365***	0.450***	0.478***
						0.0932	0.131	0.131
$(\Delta pop)_{t-2}$							-0.103*	-0.157***
							0.0551	0.0526
$(\Delta pop)_{t-3}$								0.0745
								0.0584
constant	4.922***	6.553***	0.682***	6.691***	4.631***	5.075***	4.299***	4.723***
	1.693	2.315	0.114	2.137	1.621	1.438	1.407	1.555
end-year	1860	1860	1860	1820	1880	1860	1860	1860

Standard errors in parentheses. P-values: *** p<0.01, ** p<0.05, * p<0.1
Column (2) is Prais-Orcutt. Others are OLS with Newey-West corrected standard errors.