Can't buy me sun. Exploring the relationship between climate, structural change and suicide.

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Abstract

This paper introduces climate, and more precisely, solar irradiation intensity as an important determinant of suicide rates. A theoretical model predicts that structural change of the economy has an ambiguous effect on suicide. Both solar irradiation and income decrease suicide rates. However, a shift of employment away from agriculture is expected to increase income at a price of lower actual exposure to solar irradiation. For empirical testing we construct unique data on population-weighted levels of ambient solar irradiation. Employing a CRE model for regression estimations allows to simultaneously exploit within- and between-country variation of the data. Empirical results support predictions of the theoretical model.

Introduction

World Health Organisation (WHO) considers suicide a major public health problem. More than 800.000 people die by suicide every year – around one person every 40 seconds (WHO, 2014). It occurs in all regions of the world and affects people of all ages. Even though, suicides are preventable, "*the taboo and stigma surrounding suicide persist*" (WHO, 2014, p.2). This study attempts to broaden our understanding of the problem by focusing on the importance of solar light as one of the fundamental factors causing suicide.

This paper contributes to the economic literature in several ways. First, we survey a range of medical studies to analyse biological mechanisms and determine important factors affecting suicide. Our research relies on the fact that exposure to solar irradiation can be beneficial for a number of processes in living organisms. In contrast, lack of sun can disrupt important processes in the human body, such a serotonin circulation. Once this happens, individuals become vulnerable to depression and suicide. Second, we slightly modify a classical model of suicide decisions by Hamermesh and Soss (1974) to include biological factors into analysis. Individuals lacking solar irradiation are modelled to yield lower utility from similar income, compared to the ones who do not experience such a deficit. Third, we provide empirical evidence that solar irradiation of the country's surface significantly affects its suicide rate. Our results suggest that higher average levels of short-wave irradiation are associated with lower suicide rates.

Suicide is a personal tragedy and a decision taken personally. Not a surprise that existing studies of suicide primarily focus on the individual level (Andres & Halicioglu, 2010; Case & Deaton, 2015a; Cutler et al., 2001; Daly et al., 2013; Hakko et al., 1998; Phillips et al., 2002). However, to analyse the effect of climate on suicide rates a cross-country study appears more helpful. Focusing on between-country differences allows to detect the strongest contrast in climatic conditions. We utilise geo-coded data to construct our measure of solar irradiation. Satellite images provide information on how much solar energy reaches the Earth's surface. As we are most interested in areas, where people actually live, we also account for the locations of human settlements. As a result, our measure of solar irradiation of the country's surface is weighted according to the actual distribution of its population.

This is not the first study of suicide that relies on aggregated numbers: Koo and Cox (2008), Chan et al. (2014), Madianos et al. (2014) analyse evolution of national rates; Ahlburg and Schapiro (1984), Mathur and Freeman (2002) and Case and Deaton (2015b) use the U.S. state-level data; and Becker and Woessmann (2018) provide microregional evidence from Prussia in the nineteenth century. This study combines two sources of variation in our data. Besides cross-country differences we also analyse evolution of various variables and its effect on suicide rates. Even though climate is relatively stable in our study period, the way individuals deal with it changes relatively fast. We argue that economic development is associated with substantial changes in human lifestyles and can alter the way we deal with solar irradiation. Individuals employed in agriculture are expected to spend more time abroad, thus, are more exposed to sunlight. However, as employment shifts indoors, workers spend less time under the sun. This process is supposed to increase income (extensive margin of utility), but decrease its subjective valuation (intensive margin). As a result, the overall effect of structural change on utility and, thus, suicide is ambiguous.

This article also contributes to the literature that links natural factors with health outcomes (e.g., Dalgaard and Strulik (2015, 2016)) and human behaviour (e.g., Acemoglu et al. (2001), Ashraf and Galor (2013), Spolaore and Wacziarg (2009), Strulik (2017)). Andersen et al. (2016) have used solar irradiation to explain cross-country differences in cataract prevalence and subsequent economic difference. In this paper we employ richer data on solar irradiance to explain suicide rates. We model suicide as a rational decision of utility-maximising agents, even though we assume that individuals are not always aware of the factors affecting this rationality, such as ambient solar irradiance. We use climate as an arguably exogenous force that affects biological processes in human bodies, which, in turn, affect individual decisions.

More than 75 percent of global suicides occur in low- and middle-income countries (WHO, 2014). This does not necessarily imply that developing countries have higher suicide rates, as simply more people reside there. Table 1 compares average age-standardised suicide rates for different regions. One can see that in case of males there are two regions that have significantly higher suicide rates than the rest of the world: Africa and Europe. For females Africa and South-East Asia demonstrate the highest rates. Such a mixed picture suggests that there must be different factors affecting suicide rates. Nevertheless, we see that the majority of differences between regions are significantly different from zero, implying that they are likely to be systematic. Moreover, as Table 5 demonstrates, suicide rates vary more between countries than within. In other words, we have reasons to believe that despite suicide being a personal decision, country-level rates are affected by some fundamental factors.

Figure 1 presents a more detailed geographic distribution of suicide rates. One can notice several clusters of countries with relatively high suicide rates: Eastern Europe, Sub-Saharan Africa and, to a degree, South America. Countries with high suicide rates are highly heterogeneous not only in terms of culture and economic development, but also climate. This fact suggests that even if we primarily focus on solar irradiance, we cannot ignore other factors that are expected to be deterministic for suicide rates, such as income or mortality, as will be highlighted later.

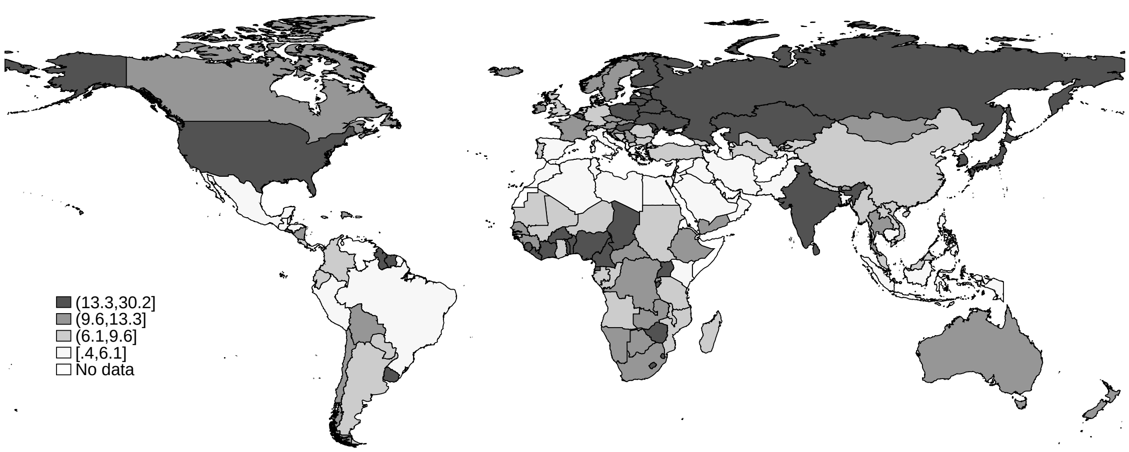
This paper is organised as follows. Section 1 summarises important findings of the medical

Table 1: Differences in average age-standardised suicide rates

Panel A: Male suicide rates						
	Africa	Americas	Eastern Mediterranean	Europe	South-East Asia	Western Pacific
Africa	–					
Americas	**-3.628**	–				
Eastern Mediterranean	**-11.716**	**-8.089**	–			
Europe	1.404	**5.032**	**13.121**	–		
South-East Asia	**-3.596**	0.032	**8.121**	**-5.000**	–	
Western Pacific	**-3.436**	0.191	**8.280**	**-4.841**	0.159	–
Panel B: Female suicide rates						
Africa	–					
Americas	**-4.251**	–				
Eastern Mediterranean	**-5.547**	**-1.296**	–			
Europe	**-3.538**	**0.713**	**2.008**	–		
South-East Asia	0.263	**4.514**	**5.809**	**3.801**	–	
Western Pacific	**-2.484**	**1.767**	**3.063**	**1.054**	**-2.747**	–

Each cell shows the difference between the line region and the column region. Regional means are calculated using data on 151 country and four years from our main dataset. Countries are grouped according to WHO classification. Bold values are statistically different from 0 at 95% confidence level.

Figure 1: Age-standardised suicide rates per 100.000 people (both sexes) in 2016



literature on suicide and incorporates them into a simple economic model. Section 2 describes the data and explains the empirical methodology of this paper. Section 3 presents the regression results. Conclusion section finalises the article.

1 Theory of suicide

1.1 Biology of suicide

Despite often being a striking event for families and friends, suicides are not always an impulsive act (WHO, 2014). Existing studies have found positive link between depression and suicide (see Beskow (1990) for a detailed summary of the literature on the topic). *Not all* suicides are complications of various mental health conditions, but, unlike impulsive acts, depression-driven suicides are better explored and we can apply some biological mechanisms already established in the literature to study cross-country variation in suicides. Moreover, stress - a factor particularly important for this study - has been found to be positively correlated both with suicide (Feskanich et al., 2002; Luscomb et al., 1980; Zhang et al., 2012) and depression (Burrows, 1977; Risch et al., 2009). Stress can be easily linked to a range of economic variables. Later in this paper we focus on income-related factors.

Besides stress, there exist other factors that make people to be more prone to suicide. One of them is sun light, that has been found to be negatively associated with suicide in the state of Victoria, Australia (Lambert et al., 2003). However, the evidence is very scarce, as studying the relationship between light and suicide is a complicated procedure. Absent the opportunity to interview a deceased person, it is hard to obtain reliable data on his or her actual exposure to light. Autopsy appears an option, but it is expensive and can be opposed by the family or friends. Nevertheless, light is also negatively associated with depression and the evidence for this relationship is broad. All events in our life provoke an influx of serotonin into the space between neurons to activate serotonin (5-hydroxytryptamine, 5-HT) receptors (Beliveau et al., 2017). Some of the 5-HT receptors are responsible for such functions as regulation of anxiety or mood (Tatarczynska et al., 2004; Young, 2007), determining if a person is happy or not. Existing studies argue that lower availability of serotonin can act as a crucial factor in depression (Kambeitz & Howes, 2015; Meltzer, 1989). A range of studies suggests that serotonin is positively associated with light. By "light" we can mean sun light in general (Lambert et al., 2002; Petridou et al., 2002; Sansone & Sansone, 2013) or more precisely defined ultra-violet radiation (UVR) (Iyengar, 1994; Zawilska et al., 2007). Moreover, bright light therapy (BLT) currently serves as an accepted treatment option for depression (Martensson et al., 2015). Both exposure to BLT (Al-Karawia & Jubair, 2016; Eastman et al., 1998; Young, 2007) or solar radiation (Eastman, 1990; Gambichler et al., 2002) can be efficient for treating various types of depression. As a result, regardless of a particular channel (direct or indirect through depression), we can expect higher levels of solar irradiance to be negatively associated with suicide rates[1].

1.2 Economics of suicide

How do economists contribute to the research of suicide? Existing economic literature often lists low incomes (Andres & Halicioglu, 2010; Daly et al., 2013; Helliwell, 2007) and unemployment (Andres, 2005; Chang et al., 2013; Jalles & Andresen, 2015) among the drivers of suicide. From a biological point of view, these can be seen as stressful life events. It is important to note that long-term states generally have stronger effect on suicide behaviour than sudden shocks (Baum, 1990). Beck et al. (1985), Kovags et al. (1975), Minkoff et al. (1973) identified a cognitive element

[1] We are aware that excessive irradiation can be harmful for human body (Lucas et al., 2006). If this had a suicide-promoting effect, regression estimates presented below would mark only the lower bound of the estimates of the true effect.

of negative expectations – namely, hopelessness – as a stronger indicator of suicidal intent than depression itself. This comes at hand for this study, as persistent events are more likely to be captured by macro-level data we use, especially when we consider income or mortality.

Individuals have different triggers of stress, especially if we consider cross-country variation. However, some factors appear important all around the World. For example, the World Values Survey indicates that more than 62 percent of the total surveyed across the world are worried about losing their job and more than 87 percent find that work plays an important role in their lives (Inglehart et al., 2014). Assuming that to an extent generalisation of preferences is reasonable, we can recall the seminal model of suicide behaviour by Hamermesh and Soss (1974). Let us slightly modify the original model to adjust it for the purpose of this study.

Individuals derive utility from income y at time m:

$$U_m = gy_m, \tag{1}$$

where $g \in (0, 1)$ determines how efficiently income converts into utility. As was mentioned above, natural factors can mediate individual perception of income and solar irradiation is one of them. In other words, marginal utility of income is affected by human biology. As a result, we expect the same level of income to yield higher utility, when solar irradiance is high (high g), and lower utility, when individuals lack solar irradiation (low g).

Costs of maintaining oneself alive, $K(a)$, increase with age, a. Summing it up, the individual's lifetime utility becomes[2]:

$$Z(a, g, y) = \int_a^\omega e^{-r(m-a)} gy_m P(m) dm - K(a), \tag{2}$$

where r is the private discount rate, ω is the highest attainable age and $P(m)$ is the probability to survive until m in this country. Equation (2) implies that variations in age structure of countries can cause a problem for a cross-country study of suicide. Older populations are expected to have a higher number of suicides, as $K(a)$ increases and gross utility left to enjoy decreases with age. For this reason, in the empirical part of the paper we will employ age-standardised suicide rates that allow us to ignore differences in age structures.

Hamermesh and Soss (1974) assume that individuals might have some taste for living, $b_i > 0$, making them refrain from suicide even when utility is negative. In terms of the whole country, this variable can include such major factors as religion or social norms. Thus, a representative individual commits suicide when:

$$Z_i(g, y) + b_i < 0. \tag{3}$$

Then the fraction of citizens who commit suicide is:

$$S(g, y) = f[-Z(g, y)], \tag{4}$$

where $f(\cdot)$ is the density function for b_i. Given that suicide is a rare outcome, it is reasonable to assume positive first and second derivatives of $f(\cdot)$.

[2]One of the major differences to Hamermesh and Soss (1974) is the way $K(a)$ is included into the lifetime utility function. In the original paper authors have included costs as a negative factor directly into utility at every moment of time m (here, in (1)), so that lifetime utility Z included lifetime maintaining costs, too. This condition prevents young individuals from committing suicide even if they are aware that at some point in the future staying alive will be extremely tough.

2 Data and methodology

Later in this paper we empirically test predictions of the model described above. For this purposes we employ a balanced panel dataset of 151 country followed over four years: 2000, 2010, 2015 and 2016. This section describes the variables that we have included in our analysis and the empirical methodology.

Existing studies do not give us a clear understanding of what particular components of light affect suicide. As was mentioned above, both bright light and solar light are used in depression therapy. The principal difference between the two sources of light is the spectrum of electromagnetic wave lengths a beam of light consists of. Sun emits a wide range of wave lengths: ultraviolet, visible light (both are shortwave radiation) and infrared (longwave). Artificial light used for indoor illumination typically has a much narrower spectrum of electromagnetic waves and consists of mostly visible light. Ultraviolet radiation actually reaching the Earth's surface is mostly filtered out by the atmosphere, but the remaining part can penetrate the skin and affect various processes in our bodies. Infrared radiation brings the Earth heat. For all wave lengths, the more energy arrives to the Earth's surface (in W/m^2), the stronger is the irradiation. As we do not know, which of the two types of solar irradiation is more important for suicide, we include both short-wave (SWI) and long-wave irradiance (LWI) into analysis.

The satellite data on actual amount of solar energy arriving to the Earth's surface (irradiance) is provided by NCEP Climate Forecast System Version 2 (CFSv2). It is available separately for short and long waves. The two types of radiation are correlated, but are not always similar (correlation coefficient in our sample is 0.7). Different types of electromagnetic waves are reflected and absorbed differently in the atmosphere (Calbo & Gonzalez, 2005). The data is provided for the whole globe in 6-hour intervals for every day starting from 1979. We aggregate all observations over one year and get an annual mean amount of irradiation a piece of land receives. The spatial resolution of the original data is quite high - 0.2 arc seconds (around 25 km at the equator). Given that for large countries within-country variance in irradiation of the surface is high, we cannot use raw means. To make the measure more adequate for the purpose of our study we calculate population-weighted values. For this, we employ the Gridded Population of the World data by the Center for International Earth Science Information Network of Columbia University. First, we multiply each unit of area by the number of people residing in it. Then, we sum these numbers across all areas within one country and divide it by the total population. As a result, the obtained value tells us how much solar energy reaches the Earth's surface in a place, where an average citizen of a country is expected to reside.

Income is measured with GDP per capita (PPP) obtained from the World Bank. ω and $P(m)$ in (2) are highly correlated: lower adult mortality increases maximum attainable age. To avoid multicollinearity we use only adult mortality rate and not life expectancy. There is a number of arguments in favour of the former variable. First of all, WHO data allows to decompose mortality rates. Suicides are included in calculation of aggregate mortality, implying presence of endogeneity. We employ mortality from all other causes besides suicide. Secondly, high adult mortality per se is a strong stress factor that can contribute to higher suicide rate. As a proxy for $K(a)$ we employ years lived with disability (YLD) from WHO - the more health deficits an individual has accumulated, the lower is the remaining lifetime utility. The model presented above assumes that individuals have some taste for living (b_i). Becker and Woessmann (2018) have demonstrated that religion could be one of the factors that influenced suicide rates in Germany. To test if religion has significant effect on suicide rates within the cross-country context we include major religion shares from Pew Research Center's Forum on Religion & Public Life (2012).

The dependent variable is age-standardised suicide rate per 100,000 people provided by WHO. As (2) suggests that older people are more likely to commit suicide, one needs to correct for demographic differences between countries using WHO standard population distribution. If a particular age group in a country is over-(under-)represented than the same group in an average world population, its mortality is down-(up-)scaled proportionately. Finally, we have to explicitly address the reliability of the data issue. Quality of vital registration systems varies across countries and numbers on ethically-sensitive topics are especially vulnerable. From statistical point of view we are likely to yield biased estimates, if suicide rates in countries with poor vital registration systems are systematically under- or over-reported. However, WHO classifies countries into four groups, according to the quality of their mortality data: countries with "1. Comprehensive vital registration with at least five years of data; 2. Vital registration with low coverage, a high proportion of indeterminate causes or no recent results; 3. Sample registration of national population; 4. No vital registration" (WHO, 2014, p. 87). Our sample includes only two countries from the third group: China and India, so for ease of interpretation we merge second and third groups. As a result in this paper we differentiate between three levels of data quality: high (countries from group 1.), medium (groups 2. and 3.) and low (group 4). In the empirical section we utilise this information in three ways. First, we test if low quality of the data is significantly associated with reported suicide rates. Second, we split the sample to keep only the countries with comprehensive vital registration systems. Third, we use the quality of the data parameter as an arbitrary weighting factor to discriminate low-quality observations. Results of these estimations are presented in the next section.

Speaking about the choice of our main estimator, unobserved heterogeneity between countries is a serious issue in the context of this study. Factors like race or religion can have significant effect on suicide, but not all of them can be controlled directly (e.g., genetics). Panel structure of our dataset allows to control for this type of heterogeneity. The standard regression specification in this case would be described by the following equation:

$$y_{it} = \beta_0 + \beta X_{it} + \lambda_t + \mu_i + \varepsilon_{it}, \tag{5}$$

where y_{it} is a suicide rate in country i at year t, a X is a vector of time-variant variables, μ_i is a country fixed effect λ_t is a year fixed effect and ε_{it} is an error term. However, our main variable of interest - solar irradiation - does not change much across the study period. Even though we have two potential sources of variation: weather fluctuations and changes in spatial distribution of people, both climate and settlement structures do not change fast. Hence, our values for solar irradiation mostly vary between countries, as Table 5 demonstrates. For this reason, we employ a correlated random effects model (CRE) (Mundlak, 1978; Wooldridge, 2000)[3]. The main advantage of this estimator is that it controls for unobserved time-invariant heterogeneity, but unlike standard fixed effects estimator allows inclusion of variables with no or little within variation. In terms of mathematical notation, we decompose a fixed effect μ_i into a vector of country-level averages $\bar{X}_i$, so that (5) changes into:

$$y_{it} = \beta_0 + \beta X_{it} + \lambda_t + \gamma \bar{X}_i + \varepsilon_{it}. \tag{6}$$

As a result, this approach allows us to control for time-invariant heterogeneity of both observed and unobserved factors. Moreover, results obtained using CRE provide us with more information: coefficients of X variables are fixed-effects (within) estimates, while coefficients of $\bar{X}_i$s are the

[3]To demonstrate that our results are not driven by the choice of the estimator we have also conducted a simple OLS analysis separately for each year. These results are presented in Table6 in the Appendix.

difference of the within and between effects: $\gamma = between - \beta$ (Mundlak, 1978; Schunck, 2013). Finally, we assume that suicide rates at the country level do not follow an autoregressive process, so no dynamic model is required (Egger & Pfaffermayr, 2005). Thus, Kuh (1959) and Houthakker (1965) argue that between effects converge to the long run effect in static panels and Egger and Pfaffermayr (2002) demonstrate that this is especially relevant for short and fat panels, like the one employed in our study.

3 Solar irradiation and suicide

This section utilises the theoretical model to formulate a list of propositions that will be empirically tested using the data and methodology described above.

Proposition 1 *Higher solar irradiation decreases suicide rate.*

Proposition 2 *Higher income level decreases suicide rate.*

For the proof of these two propositions we differentiate (4) with respect to g and y:

$$\frac{\partial S}{\partial g} = -f' \frac{\partial Z}{\partial g} \quad \text{and} \quad \frac{\partial S}{\partial y} = -f' \frac{\partial Z}{\partial y}. \tag{7}$$

Given that $-f' < 0$ and from (2) we know that a second term of each expression is positive, both derivatives can take only negative values. However, the empirical testing supports these propositions only partly, as regression results presented in Table 2 demonstrate. First of all, we see that signs of coefficients are similar for males and females. The magnitude is higher for males, but this is due to the fact that females commit suicide less, hence, female suicide rates have smaller standard deviation.

As was expected above, within coefficients of solar irradiation are not statistically significant, implying that within-country fluctuations in solar irradiance do not demonstrate significant influence on suicide. However, the mean values of both types of solar irradiation indicate significant negative effect on suicide rates. Given that within effects in Table 2 are not statistically different from zero, coefficients of mean variables could be directly treated as between effects: countries, which territory is more exposed to solar irradiation, record significantly lower suicide rates. Importantly, short-wave solar irradiation appears to be a much stronger predictor of suicide than a long-wave one. The two variables are correlated, so we expect similar effects. However, the effect of long-wave irradiation is not robust to the inclusion of a short-wave one. This gives us reasons to believe that particularly short-wave irradiation (visible and ultraviolet light) affects suicide rates, while long-wave (heat) is not influential in this context. This goes in line with the biology section, claiming that both bright light and ultraviolet are used for depression therapy. At the same time we are not aware of existing studies arguing that temperature alone is beneficial for mental health.

Interpretation of income coefficients in Table 2 is less straightforward. Negative within coefficients go in line with the Proposition 2: as a country develops (in terms of per capita income) its suicide rate decreases. However, significant positive coefficient of mean income should not be misleading. In terms of Section 2 notation, we cannot reject the null-hypothesis of $\gamma + \beta = 0$ regardless of the regression specification. Coefficients of adult mortality fully fit into the mechanism described in the theory section: if probability of dying in a given country is decreasing, it also decreases the suicide rate. Similarly, countries with lower mortality expose lower suicide rates. Moreover,

Table 2: Determinants of suicide. CRE estimates.

Dep. variable:	suicide rate					
	male			female		
	(1)	(2)	(3)	(4)	(5)	(6)
SWI	0.796		0.562	0.704		0.636
	(2.037)		(2.059)	(1.096)		(1.083)
mean SWI	-7.627***		-8.677***	-3.972***		-2.847*
	(2.898)		(3.262)	(1.460)		(1.478)
LWI		1.033*	1.010		0.314	0.282
		(0.600)	(0.614)		(0.304)	(0.287)
mean LWI		-2.824	0.815		-2.779*	-1.763
		(1.901)	(2.188)		(1.473)	(1.883)
ln(GDP_{pc})	-3.130**	-3.189**	-3.165**	-1.577***	-1.612***	-1.587***
	(1.382)	(1.371)	(1.385)	(0.535)	(0.547)	(0.537)
mean ln(GDP_{pc})	4.391***	4.721***	4.530***	1.468***	1.472***	1.401**
	(1.573)	(1.589)	(1.593)	(0.564)	(0.567)	(0.560)
adult mortality	0.046***	0.046***	0.046***	0.010**	0.010**	0.010**
	(0.011)	(0.011)	(0.011)	(0.005)	(0.005)	(0.005)
mean adult mortality	0.040***	0.040***	0.040***	0.026***	0.026***	0.026***
	(0.012)	(0.012)	(0.012)	(0.009)	(0.008)	(0.008)
YLD	-0.178***	-0.181***	-0.182***	-0.031***	-0.031***	-0.032***
	(0.044)	(0.044)	(0.045)	(0.011)	(0.011)	(0.011)
mean YLD	0.236***	0.257***	0.237***	0.042	0.053*	0.046
	(0.087)	(0.093)	(0.087)	(0.030)	(0.032)	(0.031)
lattitude	0.038	0.075**	0.038	0.001	0.011	0.001
	(0.032)	(0.036)	(0.032)	(0.014)	(0.016)	(0.014)
data quality:						
medium	-5.248***	-6.277***	-5.053**	-0.940*	-1.394**	-1.083*
	(1.941)	(2.051)	(1.973)	(0.558)	(0.591)	(0.594)
low	-9.335***	-10.147***	-9.210***	-2.571***	-2.939***	-2.678***
	(2.761)	(2.903)	(2.782)	(0.940)	(0.980)	(0.994)
religious controls	Yes	Yes	Yes	Yes	Yes	Yes
year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	604	604	604	604	604	604
Number of countries	151	151	151	151	151	151
Within. R-squared	0.356	0.358	0.358	0.268	0.267	0.268
Between. R-squared	0.586	0.564	0.588	0.509	0.506	0.517

Adult mortality and YLD stand for male mortality and male YLD in columns (1)-(3) and female mortality and female YLD in columns (4)-(6). Baseline data quality category is “high”. Standard errors clustered at the country level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

the between effect, that could also be treated as a long-term effect is almost two times larger in magnitude than the within one (short-run). This supports the hypothesis that persistent stress is a stronger predictor of suicide than non-regular stressful events. Surprisingly, within-country changes in disease burden are negatively associated with suicide rates. However, in countries with on average more YLD per capita higher suicide rates are observed. If we interpret within and between effects of YLD as short- and long-term ones, respectively, this set of results can be interpreted the following way: a temporary health shock can prevent suicide, while a more persistent condition provokes it. Finally, none of the religion shares demonstrates significant effect on suicide rates.

We also have to draw attention to data quality, as respective coefficients are significant and negative. This implies that official numbers are possibly under-reported, as countries with lower quality of vital registration systems register systematically lower suicide rates. Nevertheless, as Tables 7 and 8 demonstrate, results appear to be robust to different strategies of controlling for data quality.

3.1 Exposure to solar irradiation and suicide

So far we have focused on the climate characteristics: levels of solar irradiation of the surface. However, we have ignored the fact that *actual* exposure of the population can be different. It is natural to expect that the amount of hours spent outdoors systematically differs between countries. To help humans cope with solar irradiation, over generations skin pigmentation has been changing to adjust for the amount of ambient solar irradiation (Lucas et al., 2006). As a result, evolution has prepared people for the climatic conditions they (or rather their ancestors) face. However, the start of 20th century (even earlier in some countries) has marked rapid changes in our lifestyles. Industrialisation has driven big masses of population indoors – the environment humans were not adjusted to. This must have limited the amount of solar energy people were receiving, thus we also need to control for actual exposure to solar irradiation. As a proxy for time spent outdoors we use share of population employed in agriculture. If industrialisation has moved people away from the sun, agricultural employment must make them more exposed to solar irradiation. Even though farmers might avoid working, when solar activity is at its peak, they still have to spend substantial amount of time outdoors in the day light. At the same time, we have already seen evidence for the fact that rise in incomes increases utility and prevents suicide. Hence, we expect the effect of structural change of the economy to be more complex:

Proposition 3 *A shift of employment away from agriculture decreases suicide rate more, when solar irradiance is low, and can even increases it, when irradiance is high.*

To prove this proposition, let us redefine g from (4). Initially it was assumed to be a country-level parameter capturing the intensity of solar irradiation. Now we assume it to be a function of solar irradiance of the surface (α) and employment in agriculture (e):

$$g(\alpha, e) = \alpha e. \tag{8}$$

Solar irradiation of the surface and agricultural employment act as substitutes: low irradiance can be compensated with more hours spent outdoors. Overall effect of agricultural employment on suicide is expressed as:

$$\frac{\partial S}{\partial e} = -f\left(\frac{\partial Z}{\partial g}\frac{\partial g}{\partial e} + \frac{\partial Z}{\partial y}\frac{\partial y}{\partial e}\right). \tag{9}$$

The right-hand side of (9) can be either positive or negative, depending on the stage of development of a country:

$$\frac{\partial S}{\partial e} > 0 \quad \text{iff} \quad \frac{\partial Z}{\partial y}\frac{\partial y}{\partial e} > -\frac{\partial Z}{\partial g}\frac{\partial g}{\partial e}. \tag{10}$$

We do not assume particular shapes of several functions included into analysis, but we know that only $\partial y/\partial e$ is negative, while other components of (10) are positive. Thus, $\partial S/\partial e$ is more likely to be positive, when $\partial g/\partial e$ (namely, α) is low and $\partial y/\partial e$ is high. Overall, the effect of a decrease in agricultural employment is ambiguous. More time spent outdoors allows people to get more solar irradiation, but keeps workers away from more productive activities making them poorer. Nevertheless, we expect that in less irradiated countries individuals moving away from agriculture experience smaller loss in solar irradiation and associated marginal utility, hence, are less vulnerable to suicide.

Now we empirically analyse the overall effect of agricultural employment on country's age-standardised suicide rate. Data on employment in agriculture is provided by International Labor Organisation. According to (8), lower exposure can be compensated with higher intensity of solar irradiation, so we also include the interaction term of the two variables. To measure intensity of solar irradiation we use an average level of short-wave irradiation, that has previously demonstrated the strongest effect on suicide rates. We follow the approach suggested by Schunck (2013) and interact mean SWI with both employment in agriculture and its mean. The coefficients we present allow to estimate within and between effects. However, inclusion of interactions constrains the overall slopes of employment in agriculture and its mean separately for each country, according to a particular climatic characteristic – mean SWI level. Given that a share of employment in agriculture changes every year, we have a time-varying proxy for actual exposure to solar irradiation, despite climate (thus, mean SWI) being constant for each country. As a robustness check we also include country-level fixed effects to run a standard FE regressions. As one can see, the fixed effects results in columns (3) and (6) of Table 3 are identical to within effects of CRE estimations in columns (2) and (5), respectively. Finally, we have to note that employment in agriculture is highly correlated with per-capita GDP (correlation coefficient is -0.875), thus, we do not include the two variables into a regression simultaneously.

Results presented in Table 3 have to be interpreted cautiously. As was mentioned in Section 2, coefficients of time-varying variables represent within-country estimates. To obtain between-country effects we need to sum coefficients of time-varying variables and their country-level means. If we do so, the between-country effects of both employment in agriculture and its interaction with mean SWI appear not significantly different from zero. Moreover, within-country variation in agricultural employment alone does not have a significant effect on suicide rates. This goes in line with theoretical predictions stated above: to properly evaluate the effect of exposure to solar irradiation we also have to consider its intensity. Once we interact employment in agriculture with the mean level of short-wave irradiation, the respective coefficients become significant, especially for males.

Overall, coefficients presented in Table 3 support the theoretical prediction that as employment shifts away from agriculture, incomes rise and suicide rates decrease. However, countries that are more irradiated enjoy less of a drop in suicide rates, as structural change there is associated with greater loss in solar exposure, hence, rise in incomes translates into utility less efficiently. Figure 2 presents this mechanism graphically. Notably, in countries with mean SWI above 2.3 W/m^2 a shift of employment away from agriculture can even increase the suicide rate both for females and males. This result has to be treated cautiously, as there is only a limited number

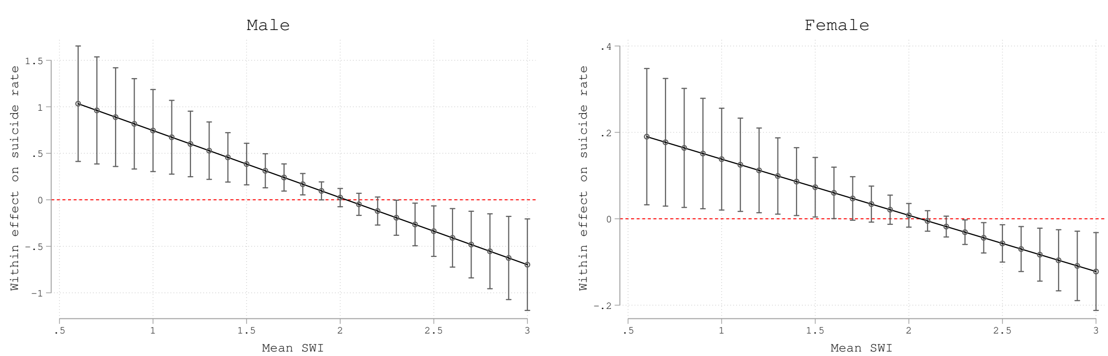
Table 3: Actual exposure to irradiation and suicide.

Dep. variable:	suicide rate					
	male			female		
Estimator:	CRE		FE	CRE		FE
	(1)	(2)	(3)	(4)	(5)	(6)
agriculture	0.054	1.466***	1.466***	0.005	0.268**	0.268**
	(0.041)	(0.459)	(0.454)	(0.014)	(0.112)	(0.111)
mean agriculture	-0.105	-1.614***		-0.026	-0.251**	
	(0.067)	(0.486)		(0.021)	(0.120)	
mean SWI	-7.021***	-8.207***		-3.168***	-2.729***	
	(2.216)	(2.474)		(0.797)	(0.761)	
agriculture × mean SWI		-0.721***	-0.721***		-0.130**	-0.130**
		(0.235)	(0.232)		(0.052)	(0.051)
mean agriculture × mean SWI		0.769***			0.111*	
		(0.240)			(0.059)	
adult mortality	0.048***	0.046***	0.046***	0.011**	0.011**	0.011**
	(0.011)	(0.010)	(0.010)	(0.005)	(0.005)	(0.005)
mean adult mortality	0.036***	0.039***		0.028***	0.029***	
	(0.012)	(0.013)		(0.010)	(0.010)	
YLD	-0.183***	-0.137***	-0.137***	-0.033***	-0.026**	-0.026**
	(0.045)	(0.031)	(0.031)	(0.011)	(0.011)	(0.011)
mean YLD	0.242***	0.186**		0.042	0.038	
	(0.088)	(0.075)		(0.031)	(0.032)	
lattitude	0.038	0.035		0.004	0.006	
	(0.031)	(0.031)		(0.013)	(0.012)	
data quality:						
medium	-5.316***	-5.098***		-0.768	-0.877	
	(1.962)	(1.977)		(0.583)	(0.572)	
low	-9.275***	-9.199***		-2.010**	-2.071**	
	(2.711)	(2.721)		(0.881)	(0.847)	
year FE	Yes	Yes	Yes	Yes	Yes	Yes
religious controls	Yes	Yes	No	Yes	Yes	No
N	604	604	604	604	604	604
Number of countries	151	151	151	151	151	151
Within. R-squared	0.343	0.426	0.426	0.230	0.256	0.256
Between. R-squared	0.584	0.584	0.128	0.516	0.517	0.141

Data on employment in agriculture, adult mortality and YLD are for males in columns (1)-(3) and females in columns (4)-(6). Baseline data quality category is "high". Standard errors clustered at the country level are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

of countries in the sample for which this is the case: Burkina Faso, Central African Republic, El Salvador, Mali, Mauritania, Namibia, Oman, Senegal, Sudan, Zimbabwe. However, this effect does not contradict with the theoretical predictions of the paper. First of all, the supposed loss in SWI associated with leaving agriculture is large. Secondly, as one can see, eight countries from the list are located in Africa. From the development literature we know that urbanisation, associated with a move of employment away from agriculture, does not necessarily increase productivity, especially if we consider African countries (e.g., Fay & Opal, 2000; Gollin et al., 2016; Jedwab et al., 2017). Furthermore, if we think about utility more broadly, not as a function of income alone, leaving agriculture could be associated with numerous hardships, e.g.: higher mortality (Brueckner, 2019), severe lack of infrastructure (Castells-Quintana, 2017), poverty (Cobbinah et al., 2015). In other words, it possible that in some countries individuals leaving agriculture decrease their marginal utility of income (due to lower sun exposure) without significant increase in well-being. As a result, the absolute change in perceived life-time utility, associated with structural transformation, can be negative.

Figure 2: Differential effects of employment in agriculture on suicide rates



Finally, we have to demonstrate that the effect of changes in agricultural employment is coming through exposure to solar irradiation and not other (supposed) channels. Previously we have mentioned that leaving agriculture can be also associated with utility-decreasing outcomes. Mortality is accounted for in our theoretical model and included in the baseline regressions. To see if rapid urbanisation increases inequality or unemployment, we include these variables into regression analysis. To measure level of inequality we employ Gini coefficients from World Inequality Database. Unemployment data is obtained from International Labor Organisation. For the sake of compactness Table 4 presents only fixed-effects regressions. Results suggest that inequality does not affect suicide rate both for males and females. Unemployment does not affect results in case of males, but in case of females our measure of irradiation exposure loses significance. This could be due to the fact that females leaving agriculture find more difficulties finding new jobs. As a result, unemployment rates increase and incomes drop, thus increasing suicide rates. However, this question has to be studied more thoroughly in the future.

Table 4: Determinants of suicide. FE estimates.

Dep. variable:	suicide rate			
	male		female	
	(1)	(2)	(3)	(4)
agriculture	2.430**	2.204***	0.699**	0.228
	(0.986)	(0.760)	(0.294)	(0.200)
agriculture × mean SWI	-1.350**	-1.138***	-0.397**	-0.113
	(0.558)	(0.390)	(0.171)	(0.107)
adult mortality	0.143***	0.076**	0.045*	0.011
	(0.030)	(0.031)	(0.024)	(0.009)
YLD	-0.094	-0.076*	-0.035*	-0.034***
	(0.061)	(0.045)	(0.018)	(0.012)
inequality	-0.047		-0.014	
	(0.167)		(0.053)	
unemployment		0.079		0.057**
		(0.083)		(0.027)
year FE	Yes	Yes	Yes	Yes
N	213	325	213	325
Number of countries	59	94	59	94
Within. R-squared	0.706	0.488	0.439	0.220
Between. R-squared	0.358	0.281	0.002	0.016

Data on employment in agriculture, adult mortality, YLD and unemployment rates are for males in columns (1)-(2) and females in columns (3)-(4). For each country included at least two data years are available. Standard errors clustered at the country level are in parentheses.* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

4 Conclusion

This article has studied the effect of solar irradiance on suicide. We further developed a theoretical model by Hamermesh and Soss (1974) that links biology and social factors to explain suicide decisions. The model predicts that higher level of exposure to solar irradiation decreases likelihood of suicide. Lack of sunlight can impede marginal utility of income, thus, decreasing individual utility and increasing the likelihood of suicide. However, income has a complex effect on suicide rates. First of all, income alone increases utility and makes staying alive a more attractive option. On the other hand, substantial rise in income is often associated with structural change of the economy. Workers previously employed in agriculture shift to occupation that are primarily located indoors. Consequently, their exposure to solar irradiation decreases, while human bodies cannot adjust to such a radical change fast. As a result, individuals yield higher income, but it translates into utility at a lower rate. The overall effect of structural change can potentially be suicide-increasing, if an associated rise in income is not high enough to compensate for a loss in solar irradiance.

The empirical testing of the model supports the theoretical predictions. Primarily relying on CRE model we exploit both between- and within-country variation in our data. We find that short-wave irradiance is negatively associated with suicide rates, while long-wave irradiance does not demonstrate robust statistically significant relationship. Moreover, within-country variation in solar irradiation does not demonstrate significant effect suicide rates, while between-country differences do. This fact implies that short-term weather fluctuations appear to be not as important as general climate. As predicted by the theoretical model, the effect of income is ambiguous. On the one hand, higher incomes increase utility, hense, decrease the likelihood of suicide. On the other hand, as employment shifts away from agriculture and incomes rise, actual exposure to solar irradiation drops. This lowers benefits of structural change and in extreme cases its overall effect can even be suicide-promoting.

Quality of the data used for empirical testing of the model varies across countries. We do not claim that this is definitely the case, but our results suggest that the number of suicide cases in countries with low quality of vital registration statistics can be systematically under-reported. This fact does not undermine the validity of the presented results, but implies that the real magnitude of the described effects can be even stronger. The data issue has to be studied explicitly in the future.

Overall, this paper presents significant evidence that net effects of structural change on well-being span far beyond a rise in incomes. The net benefits of this process can substantially vary across countries. Moreover, a rapid shift of employment away from agriculture can be harmful, especially if not compensated by a rise in incomes. Acknowledging this fact can motivate more research on the topic and assist to design a more inclusive suicide-preventing policy.

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Appendix

59 countries with data on inequality available are:
Argentina, Australia, Austria, Belgium, Bolivia, Brazil, Bulgaria, Canada, Chile, Colombia, Costa Rica, Croatia, Cyprus, Czech Republic, Denmark, Dominican Republic, Ecuado, El Salvador, Estonia, Finland, France, Georgia, Germany, Greece, Honduras, Hungary, Iceland, Ireland, Israel, Italy, Japan, South Korea, Latvia, Lithuania, Luxembourg, North Macedonia, Malta, Mexico, Netherlands, Norway, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Romania, Russian Federation, Serbia, Slovak Republic, Slovenia, South Africa, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States, Uruguay.
Data on unemployment are available for the same countries (except for Argentina, Brazil, Paraguay and Peru) and also for:
Albania, Algeria, Bangladesh, Barbados, Belarus, Belize, Bhutan, Bosnia and Herzegovina, Botswana, Cambodia, Egypt, Ghana, Guatemala, India, Indonesia, Iran, Jamaica, Jordan, Kuwait, Kyrgyz Republic, Liberia, Malaysia, Mali, Moldova, Mongolia, Morocco, Namibia, New Zealand, Pakistan, Qatar, Saudi Arabia, Sri Lanka, Suriname, Thailand, Tunisia, Ukraine, United Arab Emirates, Vietnam, Montenegro.
The main sample of 151 country includes all the countries mentioned above (including Argentina, Brazil, Paraguay and Peru) plus:
Angola, Armenia, Azerbaijan, Benin, Brunei Darussalam, Burkina Faso, Burundi, Cameroon, Cabo Verde, Central African Republic, Chad, China, Congo (Dem. Rep.), Congo (Rep.), Cote d'Ivoire,

Equatorial Guinea, Ethiopia, Gabon, the Gambia, Guinea, Guinea-Bissau, Guyana, Ira, Kazakhstan, Kenya, Lao PDR, Lebanon, Lesotho, Libya, Madagascar, Malawi, Mauritania, Mozambique, Myanmar, Nepal, Nicaragua, Niger, Nigeria, Oman, Rwanda, Senegal, Sierra Leone, Sudan, Eswatini, Tajikistan, Tanzania, Togo, Turkmenistan, Uganda, Uzbekistan, Yemen, Zambia, Zimbabwe.

Table 5: Summary statistics of used variables

Variable	Mean	Standard deviation		Min	Max
		Between	Within		
male suicide rate (per 100,000 people)	16.747	10.607	3.340	0.7	85.8
female suicide rate (per 100,000 people)	5.911	4.192	1.181	0.3	32.6
SWI (W/m^2)	1.783	0.414	0.060	0.568	3.104
LWI (W/m^2)	2.932	0.404	0.125	1.300	4.467
$\ln(GDP_{pc})$	9.131	1.200	0.210	6.351	11.695
male agriculture (% of working population)	29.568	23.530	4.970	0.2	88.3
female agriculture (% of working population)	29.588	28.868	5.676	0	96.8
male adult mortality (per 100,000 people)	215.974	108.280	35.895	62	715
female adult mortality (per 100,000 people)	148.131	104.448	34.844	33	640
male YLD (per 1000 people)	92.104	9.853	5.580	61.226	139.124
female YLD (per 1000 people)	102.228	11.795	6.288	73.265	145.401
male unemployment (% of total labour force)	8.192	5.488	2.402	0.6	31.881
female unemployment (% of total labour force)	9.791	6.745	2.412	0.457	36.026
inequality (Gini coefficient)	35.904	9.571	2.115	22	66
latitude	21.421	24.744		-42	65
religion shares (% of population):					
Christian	54.374	37.202		0.1	99.5
Muslim	26.817	37.049		0.1	99.9
unaffiliated	9.009	13.342		0.1	76.4
Hindu	2.127	9.777		0.1	80.7
Buddhist	4.642	16.729		0.1	96.9
folk	2.336	6.341		0.1	45.3
Jewish	0.648	6.143		0.1	75.6

All data is available for 151 country over 4 periods, except for unemployment (94 country, two till four periods) and inequality (59 countries, two till four periods).

Table 6: Determinants of suicide. OLS estimates.

Dep. variable:	suicide rate							
	male				female			
sample year:	2000	2010	2015	2016	2000	2010	2015	2016
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SWI	-8.997***	-5.941***	-5.270***	-5.840***	-3.728***	-3.156***	-2.790***	-2.751***
	(2.892)	(2.182)	(1.892)	(1.974)	(1.187)	(0.780)	(0.758)	(0.817)
$\ln(GDP_{pc})$	0.664	1.565*	1.274**	0.987	-0.778**	-0.184	0.312	0.246
	(0.881)	(0.838)	(0.633)	(0.610)	(0.326)	(0.361)	(0.384)	(0.373)
adult mortality	0.084***	0.087***	0.079***	0.078***	0.023***	0.032***	0.044***	0.045***
	(0.014)	(0.013)	(0.012)	(0.012)	(0.005)	(0.007)	(0.010)	(0.010)
YLD	0.075	-0.015	0.006	0.056	0.012	-0.019	-0.007	0.026
	(0.073)	(0.065)	(0.064)	(0.044)	(0.026)	(0.031)	(0.026)	(0.022)
latitude	0.071*	0.056	0.023	0.013	0.014	-0.000	-0.002	-0.008
	(0.043)	(0.035)	(0.029)	(0.029)	(0.017)	(0.015)	(0.013)	(0.014)
data quality:								
medium	-6.604***	-5.663**	-4.521**	-4.074**	-0.442	-1.215*	-1.115**	-0.961*
	(2.396)	(2.183)	(1.924)	(1.808)	(0.724)	(0.649)	(0.538)	(0.517)
low	-14.751***	-8.668***	-6.717**	-5.829**	-2.065**	-2.223**	-2.343**	-2.215**
	(3.847)	(3.029)	(2.584)	(2.391)	(0.962)	(1.037)	(0.979)	(0.882)
religious controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	151	151	151	151	151	151	151	151
Adj. R-squared	0.566	0.570	0.545	0.556	0.443	0.444	0.548	0.566

Data on adult mortality and YLD are for males in columns (1)-(4) and females in columns (5)-(8). Heteroscedasticity-robust standard errors are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Determinants of suicide in countries with comprehensive vital registration systems. OLS estimates.

Dep. variable:	suicide rate							
	male				female			
sample year:	2000	2010	2015	2016	2000	2010	2015	2016
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SWI	-12.876**	-8.550**	-9.407***	-10.138***	-2.459**	-3.105***	-2.256***	-2.400***
	(5.163)	(4.130)	(3.316)	(3.280)	(1.137)	(0.834)	(0.756)	(0.759)
$\ln(GDP_{pc})$	3.689	7.772**	5.817*	4.830*	-0.592	1.102	0.851	0.959
	(2.856)	(3.220)	(3.030)	(2.778)	(0.835)	(1.027)	(0.776)	(0.689)
adult mortality	0.184***	0.164***	0.134***	0.126***	0.026	0.037**	0.019	0.017
	(0.022)	(0.020)	(0.024)	(0.025)	(0.017)	(0.018)	(0.015)	(0.014)
YLD	0.281	0.205	0.218*	0.181*	0.153***	0.097***	0.070***	0.046**
	(0.210)	(0.151)	(0.126)	(0.102)	(0.042)	(0.033)	(0.025)	(0.019)
latitude	-0.086	-0.049	-0.059	-0.056	0.013	-0.013	-0.008	-0.011
	(0.066)	(0.054)	(0.050)	(0.048)	(0.012)	(0.016)	(0.012)	(0.012)
religious controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	55	55	55	55	55	55	55	55
Adj. R-squared	0.724	0.733	0.642	0.632	0.474	0.573	0.461	0.464

Data only from countries with comprehensive vital registration systems. Data on adult mortality and YLD are for males in columns (1)-(4) and females in columns (5)-(8). Heteroscedasticity-robust standard errors are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 8: Determinants of suicide. WLS regressions.

Dep. variable:	suicide rate							
	male				female			
sample year:	2000	2010	2015	2016	2000	2010	2015	2016
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SWI	-17.692***	-11.428***	-8.997***	-8.714***	-3.944***	-3.238***	-2.711***	-2.409***
	(4.083)	(2.634)	(1.953)	(1.894)	(0.835)	(0.576)	(0.533)	(0.523)
$\ln(\text{GDP}_{pc})$	2.410	3.923***	2.823***	2.227**	-0.629**	0.089	0.544	0.519
	(1.464)	(1.401)	(1.079)	(0.922)	(0.299)	(0.362)	(0.375)	(0.361)
adult mortality	0.092***	0.102***	0.089***	0.086***	0.017***	0.027***	0.037***	0.039***
	(0.020)	(0.019)	(0.016)	(0.014)	(0.005)	(0.006)	(0.008)	(0.008)
YLD	-0.000	-0.020	0.040	0.103**	0.044*	-0.005	0.003	0.024
	(0.090)	(0.090)	(0.079)	(0.046)	(0.026)	(0.033)	(0.023)	(0.015)
religious controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	151	151	151	151	151	151	151	151
Adj. R-squared	0.501	0.540	0.514	0.537	0.400	0.370	0.464	0.488

Observations are weighted using the following ratios: 1 for high-quality-data countries, 1/2 for middle-quality ones and 1/3 for low-quality countries. Data on adult mortality and YLD are for males in columns (1)-(4) and females in columns (5)-(8). Heteroscedasticity-robust standard errors are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$