GeoHealth

Key Points:

- We project changes in suicide incidence across the conterminous United States (U.S.) in response to warming by using six climate models
- 1–6°C of warming could result in 283–1,660 additional suicide cases annually (2015 U.S. population), a 0.7%–4.1% increase from baseline
- The greatest proportional impacts are seen in the Midwest, the North Central, the South Central, and the Southeast regions

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

C. A. Gould,
gould.caitlin@epa.gov

Author Contributions:

Conceptualization: Anna Belova, Caitlin A. Gould, Nick Obradovich, Jeremy Martinich
Data curation: Kate Munson, Madison Howell, Claire Trevisan
Formal analysis: Anna Belova, Kate Munson, Madison Howell, Claire Trevisan
Investigation: Anna Belova, Caitlin A. Gould

Projecting the Suicide Burden of Climate Change in the United States

Anna Belova[1] , **Caitlin A. Gould[2]** , **Kate Munson[1]** , **Madison Howell[1]** ,
Claire Trevisan[1] , **Nick Obradovich[3]** , and **Jeremy Martinich[2]**

[1]ICF, Inc., Fairfax, VA, USA, [2]Climate Change Division, U.S. Environmental Protection Agency, Washington, DC, USA, [3]Center for Humans and Machines, Max Planck Institute for Human Development, Berlin, Germany

Abstract   We quantify and monetize changes in suicide incidence across the conterminous United States (U.S.) in response to increasing levels of warming. We develop an integrated health impact assessment model using binned and linear specifications of temperature-suicide relationship estimates from Mullins and White (2019), in combination with monthly age- and sex-specific baseline suicide incidence rates, projections of six climate models, and population projections at the conterminous U.S. county scale. We evaluate the difference in the annual number of suicides in the U.S. corresponding to 1–6°C of warming compared to 1986–2005 average temperatures (mean U.S. temperatures) and compute 2015 population attributable fractions (PAFs). We use the U.S. Environmental Protection Agency's Value of a Statistical Life to estimate the economic value of avoiding these mortality impacts. Assuming the 2015 population size, warming of 1–6°C could result in an annual increase of 283–1,660 additional suicide cases, corresponding to a PAF of 0.7%–4.1%. The annual economic value of avoiding these impacts is $2 billion–$3 billion (2015 U.S. dollars, 3% discount rate, and 2015 income level). Estimates based on linear temperature-suicide relationship specifications are 7% larger than those based on binned temperature specifications. Accounting for displacement decreases estimates by 17%, while accounting for precipitation decreases estimates by 7%. Population growth between 2015 and the future warming degree arrival year increases estimates by 15%–38%. Further research is needed to quantify and monetize other climate-related mental health outcomes (e.g., anxiety and depression) and to characterize these risks in socially vulnerable populations.

Plain Language Summary   We project the effects of climate change on mental health in the U.S. through the end of the century by looking at potential changes to suicide rates. Separately, we estimate the U.S. population's potential willingness to pay to avoid the projected suicide impacts and to contextualize additional costs of suicide prevention. We show that, depending on increases in global temperatures, suicides in the U.S. could increase by an additional 283–1,660 cases annually. This represents a 0.7%–4.1% increase from the average 1999–2019 suicide rate and 2015 population. The largest impacts are observed in regions with higher average suicide rates from 1999 to 2019 (Northwest, North Central, and South), higher population density (Northwest, Northeast, Midwest, and South), and the largest increases in temperature and decreases in precipitation (Midwest, North Central, Northeast, and South). We estimate the annual economic value of avoiding these additional suicides could range from $2 billion to $3 billion (2015 dollars and 3% discount rate). The mental health burden of climate change is likely much greater than the impacts we report, as our analysis does not include more common indicators of poor mental health, such as depression or anxiety.

1. Introduction

Awareness and acceptance of mental illness diagnoses and treatment are becoming increasingly common in the United States (U.S.), with at least 20% of all U.S. adults diagnosed with some form of mental illness or disorder, as of 2019 (NIMH, 2021a). As individuals increasingly are exposed to and affected by climate change—either through acute- or chronic-related events—they may experience a variety of mental health effects ranging from minimal stress symptoms to clinically diagnosed disorders (Ebi et al., 2018; Hayhoe et al., 2018). For instance, long-term temperature changes are linked to greater incidences of suicide, violent or aggressive behavior, and self-reported "bad mental health days" (Basu et al., 2018; Burke et al., 2018; Mullins & White, 2019). Ranson (2014) specifically points to the projected, substantial impacts that climate change may have on different types of crime rates across the U.S. through the end of the century. More frequent or prolonged heatwaves or storms increase the amount of time that individuals spend indoors, potentially impacting mental health among

Methodology: Anna Belova, Caitlin A. Gould, Kate Munson, Madison Howell, Claire Trevisan, Nick Obradovich
Project Administration: Caitlin A. Gould, Jeremy Martinich
Resources: Jeremy Martinich
Supervision: Caitlin A. Gould, Jeremy Martinich
Validation: Jeremy Martinich
Visualization: Anna Belova
Writing – original draft: Anna Belova, Caitlin A. Gould, Kate Munson, Madison Howell, Claire Trevisan, Jeremy Martinich
Writing – review & editing: Anna Belova, Caitlin A. Gould, Kate Munson, Nick Obradovich

those who use the outdoors for exercise and stress management (Dodgen et al., 2016). Extreme weather events such as droughts, wildfires, heavy rainfall, floods, tropical cyclones, and storm surges are connected to adverse mental health effects, including post-traumatic stress disorder (PTSD), depression, and other types of mood disorders, generalized anxiety disorders, and an increased incidence of aggressive behavior and violence (Dodgen et al., 2016; Vins et al., 2015).

Concerns about mental health and compounding factors like climate change are especially relevant when considering specific outcomes such as suicide and the costs associated with mental healthcare. In considering suicide as an indicator of poor mental health, the statistics are especially stark. In 2018, suicide was the tenth leading cause of death in the U.S. (NIMH, 2021b). In 2019, the age-adjusted suicide incidence rate was 13.9 deaths per 100,000 (CDC 2021). Furthermore, treatment and program costs for mental health support services in the U.S. have been increasing over time. One analysis shows that treatments associated with mental health in the U.S., including substance misuse disorders, amounted to $187.8 billion in 2013, having increased at an annual rate of 3.7% between 1996 and 2013 (values reported in 2015 U.S. dollars; Dieleman, 2016). The U.S. Substance Abuse and Mental Health Services Administration's 2021 fiscal year budget plan allocated $1.7 billion toward mental health programs, including children's mental health services, certified community behavioral health clinics, and protection and advocacy efforts for individuals with mental illness, which is an increase of $144 million since 2019 (HHS, 2021).

We contribute to and expand the understanding of the relationships between climate change, mental health, and monetized societal burden by using suicide as an outcome of interest. We quantify and monetize county-scale mental health impacts in the conterminous U.S. (e.g., excluding Alaska, Hawaii, and U.S. territories) associated with 1−6°C of warming across the country relative to a 1986–2005 climate baseline. This study was conducted using inputs and assumptions consistent with the U.S. Environmental Protection Agency (EPA)'s (EPA) Climate change Impacts and Risk Analysis (CIRA) 2.0 project, a multi-sector modeling framework to quantify and monetize climate change impacts in the U.S. (Martinich & Crimmins, 2019). We focus on suicide as the only mental health outcome for which we found both robust marginal temperature impact estimates that are representative of the U.S. (Burke et al., 2018; Kim et al., 2019; Mullins and White, 2019) and information to support economic valuation of damages associated with elevated health risk (U.S. EPA, 2010). We develop our estimates using downscaled temperature and precipitation projections for 2006–2100 from six global climate models based on arrival years across the conterminous U.S. (GCM; USBR, 2016) and suicide rate estimates for 1999–2019 from the U.S. National Vital Statistics System ("NVSS"; CDC, 2021), county-scale population projections using the EPA's Integrated Climate and Land Use Scenarios (ICLUS) v2 model (U.S. EPA, 2017b), and the EPA's Value of a Statistical Life ("VSL", U.S. EPA, 2010). We characterize uncertainty in our results using Monte Carlo methods and evaluate the relative importance of quantifiable uncertainty sources.

2. Materials and Methods

We have reviewed literature published from 2010 to 2020 on the relationships between climate change and mental health in the U.S. and identified several studies that reported nationally representative estimates suitable for the U.S.-wide impact estimation (see Section S1 in Supporting Information S1 for details on literature reviewed). Three studies have evaluated the relationship between suicide incidence and temperature in the U.S. using cause-specific mortality incidence data from the U.S. Centers for Disease Control and Prevention (CDC) NVSS, and Parameter-elevation Regressions on Independent Slopes Model (PRISM) or National Climatic Data Center (NCDC) climate data (Burke et al., 2018; Kim et al., 2019; Mullins & White, 2019). Three studies have evaluated the relationship between the incidence of self-reported bad mental health days (BMHD) over a 30-day period and temperature in the U.S. using Behavioral Risk Factor Surveillance System (BRFSS) survey results and PRISM climate data (Li et al., 2020; Mullins & White, 2019; Obradovich et al., 2018).

Research on climate and other mental health endpoints, such as mental health hospitalizations (Schmeltz & Gamble, 2017), emergency room visits (Basu et al., 2018; Mullins & White, 2019), depression (Kioumourtzoglou et al., 2017), and self-reported worsening mental health (Barreau et al., 2017), has not relied on nationally representative U.S. data; the results of these studies could not be used to support our analysis. Because objectives of our analysis include monetizing the climate change-related burden of mental illness, we have further excluded

the evaluation of climate impacts on the incidence of BMHD, for which we have not located economic valuation studies measuring willingness to pay to avoid BMHD in the U.S. population.

Table 1 summarizes the methods and data used to quantify and monetize conterminous U.S. county-scale suicide incidence impacts associated with 1–6°C of warming relative to a 1986–2005 climate baseline. Panel A shows estimates of the temperature-suicide relationship that we have selected for integrated model development. The health impact functions derived from these estimates, along with the sampling uncertainty characterization, are shown in Panel B. Panel C contains a summary of input data required for the public health impact estimation, while Panel D describes input data required for economic valuation. Below we provide additional details on the modeling components in Table 1 and describe methods used for modeling uncertainty analysis.

2.1. Health Impact Functions

Similar effect magnitudes have been estimated by studies that have taken advantage of random variation in temperature over time and across U.S. locations to identify the causal effect of changes in temperature on the suicide rate (Burke et al., 2018; Kim et al., 2019; Mullins & White, 2019). Burke et al. (2018) report a +0.68% monthly suicide incidence rate per +1°C in mean monthly temperature. Mullins and White (2019) report a +0.35% monthly suicide incidence rate per +1°F in mean monthly temperature, which is equivalent to +0.63% per +1°C. Kim et al. (2019) report the equivalent of a 0.08% monthly suicide incidence rate per +1°C using relative risk. For health impact function development, we rely on results in Mullins and White (2019) because their evaluation is based on more recent data with larger geographical coverage (See Section S1 in Supporting Information S1 for details on study selection). To represent model specification uncertainty of our mental health impacts the extrapolation model, we have chosen the following four specifications:

1. The baseline binned specification was evaluated by Mullins and White (2019)
2. The binned specification adjusted for 2-month temporal displacement. While Mullins and White (2019) conclude that their results do not support the temporal displacement hypothesis (the hypothesis that hot temperatures in a given month increase suicides in that month and decrease them in the following month) based on the analysis of 2-month to 6-month exposure windows, their results for the 2-month exposure window are consistent with the temporal displacement as described and tested in Burke et al. (2018). Furthermore, Burke et al. (2018) used the temporal displacement-adjusted results for climate change health impact projections in their study
3. The linear specification was chosen because all three identified studies on suicide rate and temperature in the U.S. conclude that the linearity of this relationship is likely
4. The linear specification that incorporates temperature and precipitation effects was considered because Mullins and White (2019) find that precipitation is a statistically significant contributor

Because of the extensive missing data imputation used in the earlier years of the full Mullins and White (2019) analysis time period 1960–2016, we use estimates based on the data for the most recent time period reported in Mullins and White (2019): 1989–2016 data for specifications (1)–(3) and 1979–2011 data for specification (4).

2.2. Climate Projections

Downscaled climate projections for the U.S. are based on the Localized Constructed Analogs (LOCA) data set (Pierce et al., 2014), which includes daily minimum and maximum temperature and daily precipitation projections for 32 GCMs at the 1/16th degree spatial resolution (USBR, 2016). We generate model-specific projections for CanESM2, CCSM4, GFDL-CM3, GISS-E2-R, HadGEM2-ES, and MIROC5 to follow the CIRA2.0 framework. These GCMs reasonably represent the range of temperature and precipitation outcomes for the conterminous U.S. found in the broader ensemble, and the subset also includes a consideration of model skill and independence. Historical climate data are drawn from a 1/16th degree gridded reanalysis data set, which uses meteorological station data across the conterminous U.S. (Livneh et al., 2015).

We use six different GCMs in order to explore the sensitivity of these results to differences in spatial patterns of future warming and precipitation, even when controlling for national average temperature change. We evaluate impacts from an 11-year projection window at each integer degree of warming relative to a baseline of 1986–2005, the same reference period used in the Fourth National Climate Assessment (Hayhoe et al., 2018; Martinich

Table 1
Summary of Climate Change-Attributable Mental Health Impacts Model—Table 1 Summarizes the Methods and Data Used to Quantify and Monetize Conterminous U.S. County-Scale Suicide Incidence Impacts Associated With 1–6°C of Warming Relative to a 1986–2005 Climate Baseline

Modeling details	Alternative specifications			
	Binned	Binned with displacement	Linear	Linear with precipitation
Panel A: Specification details				
Mullins & White (2019) reference	Table 2, Column: Suicide 1989–2016	Table A3, Column: 2 Months	Table 2, Column: Suicide 1989–2016	Table A7, Column: Suicide 1979–2011
Effect specification	$dIR/IR = \beta_{<30}dD^{<30} + \beta_{30:40}dD^{30:40} + \beta_{40:50}dD^{40:50} + \beta_{50:60}dD^{50:60} + \beta_{70:80}dD^{70:80} + \beta_{>80}dD^{>80}$		$dIR/IR = \alpha_T dT^{\circ F}$	$dIR/IR = \alpha_T dT^{\circ F} + \alpha_P dP^{in.}$
Coefficient (Standard Error)[a]	$\beta_{<30} = -0.59\,(0.07)$ $\beta_{30:40} = -0.27\,(0.07)$ $\beta_{40:50} = -0.21\,(0.06)$ $\beta_{50:60} = -0.18\,(0.05)$ $\beta_{70:80} = 0.16\,(0.04)$ $\beta_{>80} = 0.32\,(0.08)$	$\beta_{<30} = -0.54\,(0.07)$ $\beta_{30:40} = -0.16\,(0.08)$ $\beta_{40:50} = -0.11\,(0.09)$ $\beta_{50:60} = -0.16\,(0.07)$ $\beta_{70:80} = 0.13\,(0.07)$ $\beta_{>80} = 0.26\,(0.10)$	$\alpha_T = 0.44\,(0.04)$	$\alpha_T = 0.41\,(0.06)$ $\alpha_P = -0.16\,(0.07)$
Notation	*IR*—Monthly suicide incidence rate per 100,000; $D^{<30}$—Number of days per month with average daily temperature <30°F; $\beta_{<30}$—Marginal percent change in *IR* due to a unit increase $D^{<30}$; $D^{30:40}$—Number of days per month with average daily temperature in 30–40°F; $\beta_{30:40}$—Marginal percent change in IR due to a unit increase $D^{30:40}$; $D^{40:50}$—Number of days per month with average daily temperature in 40–50°F; $\beta_{40:50}$—Marginal percent change in *IR* due to a unit increase $D^{40:50}$; $D^{50:60}$—Number of days per month with average daily temperature in 50–60°F; $\beta_{50:60}$—Marginal percent change in *IR* due to a unit increase $D^{50:60}$		$D^{70:80}$—Number of days per month with average daily temperature in 70–80°F; $\beta_{70:80}$—Marginal percent change in *IR* due to a unit increase $D^{70:80}$; $D^{>80}$—Number of days per month with average daily temperature >80°F; $\beta_{>80}$—Marginal percent change in *IR* due to a unit increase $D^{>80}$; $T^{\circ F}$—Average monthly temperature (°F); α_T—Marginal percent change in *IR* due to a unit increase $T^{\circ F}$; P^{in}—Cumulative monthly precipitation (in.); α_P—Marginal percent change in *IR* due to a unit increase $P^{in.}$.	
Panel B: Health impact function details				
Functional form	$\Delta I_{cyas} = N_{cyas} \sum_m \frac{IR_{cmas}}{100,000} \cdot \frac{1}{100} \cdot [\beta_{<30}(D^{<30}_{cym} - D^{<30}_{cbm}) + \beta_{30:40}(D^{30:40}_{cym} - D^{30:40}_{cbm}) + \beta_{40:50}(D^{40:50}_{cym} - D^{40:50}_{cbm}) + \beta_{50:60}(D^{50:60}_{cym} - D^{50:60}_{cbm}) + \beta_{70:80}(D^{70:80}_{cym} - D^{70:80}_{cbm}) + \beta_{>80}(D^{>80}_{cym} - D^{>80}_{cbm})]$		$\Delta I_{cyas} = N_{cyas} \sum_m \frac{IR_{cmas}}{100,000} \cdot \frac{1}{100} \cdot \alpha_T \frac{9}{5}(T^{\circ C}_{cym} - T^{\circ C}_{cbm})$	$\Delta I_{cyas} = N_{cyas} \sum_m \frac{IR_{cmas}}{100,000} \cdot \frac{1}{100} \cdot [\alpha_T \frac{9}{5}(T^{\circ C}_{cym} - T^{\circ C}_{cbm}) + \alpha_P \cdot 0,03937 \cdot (P^{mm}_{cym} - P^{mm}_{cbm})]$
Notation[b]	*C*—U.S. county index; *y*—Modeled arrival year; *b*—Modeled baseline year; *a*—Age group index; *s*—Sex category index;		*I*—Annual suicide incidence; *N*—Population size; $T^{\circ C}$—Average monthly temperature (°C); P^{mm}—Cumulative monthly precipitation (mm).	
Sampling uncertainty characterization[c]	$\beta_{<30} \sim N(-0.59, 0.07)$ $\beta_{30:40} \sim N(-0.27, 0.07)$ $\beta_{40:50} \sim N(-0.21, 0.06)$ $\beta_{50:60} \sim N(-0.18, 0.05)$ $\beta_{70:80} \sim N(0.16, 0.04)$ $\beta_{>80} \sim N(0.32, 0.08)$	$\beta_{<30} \sim N(-0.54, 0.07)$ $\beta_{30:40} \sim N(-0.16, 0.08)$ $\beta_{40:50} \sim N(-0.11, 0.09)$ $\beta_{50:60} \sim N(-0.16, 0.07)$ $\beta_{70:80} \sim N(0.13, 0.07)$ $\beta_{>80} \sim N(0.26, 0.10)$	$\alpha_T \sim N(0.44, 0.04)$	$\alpha_T \sim N(0.41, 0.06)$ $\alpha_P \sim N(-0.16, 0.07)$
Panel C: Input data for health impact functions				
Climate stressors	Month-specific and temperature bin-specific number of days		Month-specific average temperature (°C)	Month-specific average temperature (°C) Month-specific cumulative precipitation (mm)
Baseline suicide rate	Month-specific suicide rate per 100,000 by U.S. county, age group, and sex			
Population size	Projected population size by U.S. county, age group, and sex			

Table 1
Continued

Panel D: Economic valuation	
Economic value estimation	$V_{cyas} = \Delta I_{cyas} \cdot VSL_y$
VSL	$VSL_y = VSL_o \cdot \left(\frac{M_y}{M_o}\right)^{\varepsilon}$
Notation[d]	VSL_y—Projected VSL; M_y—Future U.S. income per capita; VSL_o—Base VSL; M_o—U.S. income per capita corresponding to the year of the base VSL estimate. ε – VSL income elasticity;
Base VSL parameter	The base VSL (millions of 1990 U.S. dollars and 1990 income per capita year) uncertainty is to be characterized by the Weibull distribution (location $= 0$, scale $= 7.75$, and shape $= 1.51$). The central tendency of the VSL uncertainty distribution is $4.8 million (1990 U.S. dollars and 1990 income per capita year). This distribution is recommended for use in EPA regulatory impact analyses (U.S. EPA, 2010).
VSL income elasticity parameter	The VSL income elasticity uncertainty is to be characterized using the Triangular distribution (lower limit $= 0.08$, mode $= 0.4$, upper limit $= 1$). The central tendency of the VSL income elasticity distribution is 0.4. This distribution is recommended for use in EPA regulatory impact analyses (U.S. EPA, 2010).
Income per capita growth	Historical (1990–2018; The World Bank, 2010) and projected U.S. income per capita for each evaluation year (2010–2100; obtained from the EPA 2/2/2021)

Note. Panel A shows estimates of the temperature-suicide relationship that we have selected for integrated model development. The health impact functions derived from these estimates, along with the sampling uncertainty characterization, are shown in Panel B Panel C contains a summary of input data required for public health impact estimation, while Panel D describes input data required for economic valuation.

F, degrees Fahrenheit; C, degrees Celsius; mm, millimeters; in, inches; VSL, value of a statistical life; EPA, U.S. Environmental Protection Agency.

[a]Coefficients in the referenced tables were multiplied by 100 to reflect percent changes. [b]This notation is incremental to the Notation row in Panel A. [c]Note that this sampling uncertainty characterization assumes that there is no correlation across marginal effects. [d]This notation is incremental to the Notation rows in Panels A and B.

& Crimmins, 2019). Each integer degree of warming is defined as an increase of 1°C of average annual temperature in the conterminous U.S. above the baseline. The temperature changes modeled in this analysis are assumed to be gradual throughout the century, rather than occurring in accelerated rates of change at varying points. The GCM-specific arrival years of each of these integer degrees of warming are calculated under the Representative Concentration Pathway (RCP) 8.5 (see Table S2 in Supporting Information S1). Each arrival year is represented by data from the projected time horizon that includes 11 years surrounding it (e.g., an arrival year of 2011 has a projected time horizon of 2006–2016). For certain integer degrees of warming, several models project arrival years after 2100. These cases are excluded from the analysis as LOCA data do not include temperature and precipitation projections beyond 2100. RCP 8.5 is the preferred scenario for this analysis because it can be used to assess mental health impacts associated with a wide range of future temperatures, including higher levels of warming (e.g., 5°C) that would not be reached by the end of the century under lower-emission scenarios. The selection of RCP 8.5 in this study does not imply a judgment regarding the likelihood of that scenario.

Daily average temperatures and monthly precipitation reported for the future and baseline time periods are calculated as an average of daily temperature for each day in the year and an average of cumulative precipitation for each month for all years in the time horizon. Baseline values of climate metrics are calculated based on a 20-year time horizon (1986–2005), whereas future values of climate metrics are calculated based on an 11-year time horizon surrounding each arrival year. Baseline values of climate metrics are calculated using the historical Livneh gridded reanalysis data set, and future values of climate metrics are calculated using the LOCA downscaled data set. County-level climate projections are derived from gridded projections using population size-based weighting (Section S2 in Supporting Information S1).

2.3. Suicide Incidence Rates

We use 1999–2019 suicide incidence rate data by using a ten-year age group, sex, and county for all U.S. counties from the U.S. Centers for Disease Control and Prevention (CDC, 2021) Underlying Cause of Death database (underlying cause of death ICD-10 codes: X60–X84). When the number of reported suicide deaths within a county, age group, and sex category is below 20, CDC tags the corresponding death rate estimate as "unreliable". In these circumstances, we use the state and rurality-specific counts of suicide deaths within the corresponding age group and sex category as proxies for unreliable county-specific data. We rely on rurality-specific incidence data following

findings that suicide among youth occurs at higher rates in smaller, more rural areas than in larger, more urban areas (Ivey-Stephenson et al., 2017; Kegler et al., 2017). Because the health impact functions rely on monthly suicide rate estimates, we distribute annual suicide rates throughout the year using monthly age group- and sex- category-specific suicide incidence rate data at the national level data (Section S2 in Supporting Information S1).

2.4. Population Projections

We use county-scale population projections for 2010–2100 from the EPA's ICLUS v2 model (Bierwagen et al., 2010; U.S. EPA, 2017b). The population projections reflect no climate change (NOCC) scenario population estimate, where the 1970–1999 average climate is held constant for all years. The spatial pattern of population change in ICLUS v2 relies on assumptions regarding fertility, migration rate, and international immigration based on the Shared Socioeconomic Pathway (SSP) 2, which suggests medium levels of fertility, mortality, and international immigration (O'Neill et al., 2014). Whereas global emissions under SSP2 are not large enough to meet a radiative forcing of 8.5 W/m^2, the SSP2 pathway yields a more plausible U.S. population projection (∼450 million by the end of the century) within the ICLUSv2 model compared to SSP5 (∼740 million). Along with county-level total population data, the ICLUS v2 data set includes a national-level 5-year age group and sex category-specific population projections. Because suicide incidence varies significantly by sex and age group (Table S2 in Supporting Information S1), we use national estimates of the age group- and sex category-specific future populations to distribute the projected future county-level total population by age and sex. To assess the influence of population growth on the future climate change-attributable annual number of suicides, we generate estimates under two scenarios. The first scenario allows for county-level population growth between 2015 and the GCM-specific arrival year, while the second scenario uses a static 2015 population. We use the 2015 population for these comparisons to maintain consistency with the CIRA 2.0 project (U.S. EPA, 2017a).

2.5. Economic Valuation

The VSL is used to estimate the U.S. population's collective willingness to pay to avoid climate change-related increases in suicide risk. This is a common valuation metric used in climate economics (National Academies, 2017), and we follow the EPA (2010) guidelines to obtain a VSL suitable for valuation of mortality risk changes during 2015–2100. As the base value, we use the VSL estimate of $4,800,000 (1990 U.S. dollars and 1990 income per capita year), which is the central tendency of the VSL uncertainty distribution recommended for use in EPA regulatory impact analyses (U.S. EPA, 2010). We adjust the base VSL estimate for inflation to 2015 U.S. dollars and for growth in U.S. income per capita over time. This adjustment combines both historical and projected data on income growth as well as an estimated VSL income elasticity of 0.4, recommended for this purpose by the EPA (U.S. EPA, 2010; see Section S2 in Supporting Information S1 for details on income growth and inflation adjustments). We quantify valuation uncertainty using EPA's distributions for base VSL and VSL income elasticity (see Table 1 Panel D). To assess the influence of income growth on the monetized suicide burden of climate change, we compare estimates that allow for income growth between 2015 and the GCM-specific arrival year and estimates that use 2015 income per capita regardless of the arrival year. To express all future economic values in present terms, we apply a 3% discount rate, which is a social rate of time preference recommended for use in U.S. regulatory analyses (OMB, 2003).

2.6. Uncertainty Analysis

Our modeling involves several quantified sources of uncertainty: climate modeling uncertainty in temperature and precipitation projections, specification uncertainty of the climate-suicide relationship, the sampling uncertainty for the associated climate-suicide parameter estimates, and economic valuation uncertainty. To characterize the impact of these uncertainty sources, we rely on sensitivity analyzes for sources that are not characterized by probability distributions (e.g., climate modeling and climate-suicide relationship specification uncertainty) and on sampling-based uncertainty analysis for parameters characterized by uncertainty distributions (i.e., health impact function coefficients and VSL). For the sampling-based uncertainty analysis, we have used a Monte Carlo simulation with Latin Hypercube sampling from 50 equiprobable intervals with two draws per interval. To understand the drivers of uncertainty, we compute standardized rank regression coefficients (SRRCs) for each source (Saltelli et al., 2000). SRRCs are obtained from a regression of warming degree-, sex-, age group-, state-, and sampling iteration-specific monetized outcome rank on ranks of the corresponding uncertainty and

Table 2
Climate Change-Attributable Suicide in the United States

Scenario/Source of uncertainty	Metric	Degrees Celsius above baseline for average U.S. temperature					
		1°C	2°C	3°C	4°C	5°C	6°C
Panel A: Overall U.S. annual impact							
2015 population and 2015 income	Cases[a]	283 (249–314)	563 (491–624)	851 (740–942)	1,120 (971–1,240)	1,380 (1,190–1,530)	1,660 (1,430–1,850)
	Undiscounted value[b] (millions 2015 USD)	2,880 (682–10,100)	5,730 (1,360–20,200)	8,650 (2,060–30,500)	11,400 (2,720–40,300)	14,000 (3,350–49,600)	16,900 (4,050–59,800)
	PDV[b] (3%, millions 2015 USD)	2,840 (673–9,980)	3,060 (726–10,800)	2,700 (643–9,530)	2,640 (630–9,310)	2,280 (547–8,090)	2,100 (505–7,450)
Panel B: U.S. Annual impact sensitivity to assumptions about population and income growth							
Future population	Cases[a]	282 (248–313)	648 (565–717)	1,060 (923–1,180)	1,450 (1,250–1,610)	1,850 (1,600–2,060)	2,290 (1,970–2,560)
Future population and 2015 income	PDV[b] (3%, millions 2015 USD)	2,870 (668–9,900)	3,490 (830–12,300)	3,330 (795–11,800)	3,390 (811–12,000)	3,050 (732–10,800)	2,890 (696–10,300)
Future population and future income	PDV[b] (3%, millions 2015 USD)	2,820 (668–9,920)	3,970 (919–15,400)	4,190 (1,010–17,600)	4,510 (1,120–19,500)	4,300 (1,090–19,300)	4,270 (1,110–19,900)

Note. Table 2 presents our estimates of suicide impacts of climate change in the U.S. in terms of annual attributable cases and present discounted value (PDV, at 3% discount rate) by warming degree above baseline U.S. average temperature. Table 2, Panel A, shows overall annual impacts computed assuming 2015 population size and 2015 income levels, with simulation results averaged over 24 projections based on six GCMs and four health impact function specifications. Table 2, Panel B, shows the sensitivity of our results to assumptions about population and income growth. PDV, present discounted value; USD, U.S. dollars; NA, not available.
[a]Annual number of suicides attributable to change in climate corresponding to a warming degree. The range in parentheses captures the 90% confidence interval. [b]Annual value of avoiding suicides attributable to change in climate corresponding to a warming degree. The ranges in parentheses capture the 90% confidence interval.

variability sources. The rank-based regression facilitates comparisons of relative input importance for nonlinear input combinations.

3. Results

Table 2 presents our estimates of suicide impacts of climate change in the U.S. in terms of annual attributable cases and present discounted value (PDV, at 3% discount rate) by warming degree above the baseline U.S. average temperature. Table 2, Panel A, shows overall annual impacts computed assuming 2015 population size and 2015 income levels, with simulation results averaged over 24 projections based on six GCMs and four health impact function specifications. Warming of 1–6°C could result in an annual increase of 283 (CI 90%: 249–314)–1,660 (CI 90%: 1,430-1,850) suicide cases, with impacts growing monotonically. The economic value of avoiding these impacts is $2.1 (CI 90%: $0.505–$7.45) billion–$3.06 (CI 90%: $0.726–$10.8) billion (2015 U.S. dollars, 3% discount rate, and 2015 income level), with the highest value observed at 2°C of warming, after which future arrival year-related discounting starts to outweigh the increase in the number of annual cases. Table 2, Panel A, also reports the undiscounted economic value, which, in absence of discounting effects, is increasing with the number of annual suicide cases.

Table 2, Panel B, shows the sensitivity of our results to assumptions about population and income growth. There are no appreciable differences in results for 1°C of warming because four out of six GCMs with arrival years are occurring prior to 2015, while the arrival years for the remaining two GCMs are 2017 and 2025 (see Table S2 in Supporting Information S1). For warming of 2–6°C, we estimate an annual population growth-adjusted increase of 648 (CI 90%: 565–717)–2,290 (CI 90%: 1,970–2,560) suicide cases, which is 15%–38% larger than annual suicide increases estimated using 2015 population size. At 2015 income level and for warming of

2–6°C, the economic value of avoiding the population growth-adjusted impacts is $2.89 (CI 90%: $0.696–$10.3) billion–$3.49 (CI 90%: $0.83–$12.3) billion, with PDV peaking at 2°C of warming. When income growth is considered, the economic value of avoiding the population growth-adjusted impacts for warming of 2–6°C is $3.97 (CI 90%: $0.919–$15.4) billion–$4.51 (CI 90%: $1.12–$19.6) billion, with PDV peaking at 4°C. For warming of 2–6°C, population and income growth-adjusted PDV estimates are 30%–103% larger than those estimated at 2015 population size and 2015 income level and 14%–48% larger than those estimated at future population size and 2015 income level.

Table S6 in Supporting Information S1 shows the sensitivity of our estimates to the choice of GCM (Panel A) and the choice of health impact function specification (Panel B). The largest estimates of annual suicide increases are generated using GFDL_CM3 and HadGEM2_ES, whereas the smallest estimates are generated using CCSM4 and MIROC5. Larger estimates are generated by models that project higher warming for counties with larger baseline suicide rates, population size, and larger share of males and the elderly (see Figures S1–S3 in Supporting Information S1). The binned temperature specification of the health impact function generates 7% smaller estimates compared to the linear temperature specification. Accounting for displacement decreases the binned temperature specification-based estimates by 18%, whereas precipitation decreases the linear specification-based estimates by 7%. Table S7 in Supporting Information S1 shows the SRRC estimates that illustrate the influence of uncertainty (health impact function coefficients and VSL) and variability (population size, incidence rate, and climate) on PDV. The largest drivers of PDV magnitude are the suicide rate and population size, followed by VSL. The least influential drivers are climate variability and health impact function coefficient uncertainty. These drivers are of similar magnitude for linear specifications, but for binned specifications, climate variability is more influential than health impact function coefficient uncertainty.

Figure 1 shows spatial patterns in the conterminous U.S. climate change-attributable suicide impact estimates. Panels (a) and (b) show annual excess number of suicides by county for 1°C and 3°C of warming, respectively. The largest effects are seen in regions (USGS, n.d.) with higher baseline suicide rates (the Northwest, the North Central, and the South; Figure S1 in Supporting Information S1 panel (b)), higher population density (the Northwest, the Northeast, the Midwest, and the South; Figure S1 in Supporting Information S1 panel (a)), and the largest increases in temperature and decreases in precipitation (the South, the Midwest, the North Central, and the Northwest; Figures S2–S4 in Supporting Information S1). Panels (c) and (d) standardize the spatial patterns with respect to population size and highlight impacts from climate change and baseline suicide rates. In this case, the Northwest, the North Central, the Midwest, and the South continue to exhibit the larger impacts, while impacts in the Northeast are less pronounced. Panels (e) and (f) further normalize the spatial patterns with respect to the baseline suicide rate, revealing that the largest proportional changes in suicide incidence are to be expected in the Midwest, the North Central, the South Central, and the Southeast.

4. Discussion

This study builds on climate and suicide-focused mental health research to quantify and monetize changes in annual suicide incidence across the U.S. in response to global warming between 1 and 6°C. We present estimates by the degree of warming to decouple the impacts of changing climate from the impacts of timing, scenario, or climate model used to develop the estimate (Sarofim et al., 2021). Averaging over 24 projections (based on six global climate models and four health impact functions) and assuming the 2015 population size, 1–6°C of warming could result in an annual increase of 283 (CI 90%: 249–314)–1,660 (CI 90%: 1,430–1,850) additional suicide cases. This is a 0.6%–4.1% increase from the 40,500 suicides expected in the U.S. annually in the absence of warming, based on the 2015 population size and 1990–2019 suicide incidence rates. The annual economic value of avoiding these impacts is $2.1 (CI 90%: $0.504–$7.45) billion–$3.06 (CI 90%: $0.726–$10.8) billion (2015 U.S. dollars, 3% discount rate, 2015 income level). Population and income growth between 2015 and warming degree arrival time affects our range of estimates to an increase of 282 (CI 90%: 248–313)–2,290 (CI 90%: 1,970–2,560) additional suicide cases per year, avoiding which would potentially be valued at $2.82 (CI 90%: $0.668–$9.92) billion–$4.51 (CI 90%: $1.12–$19.5) billion by the U.S. population.

Despite distinct methodological differences, our results are comparable to those reported in Burke et al. (2018), who relied on the RCP 8.5 scenario projections from 30 global climate models and United Nations population projections to estimate the cumulative number of U.S. suicides attributable to temperature increases during
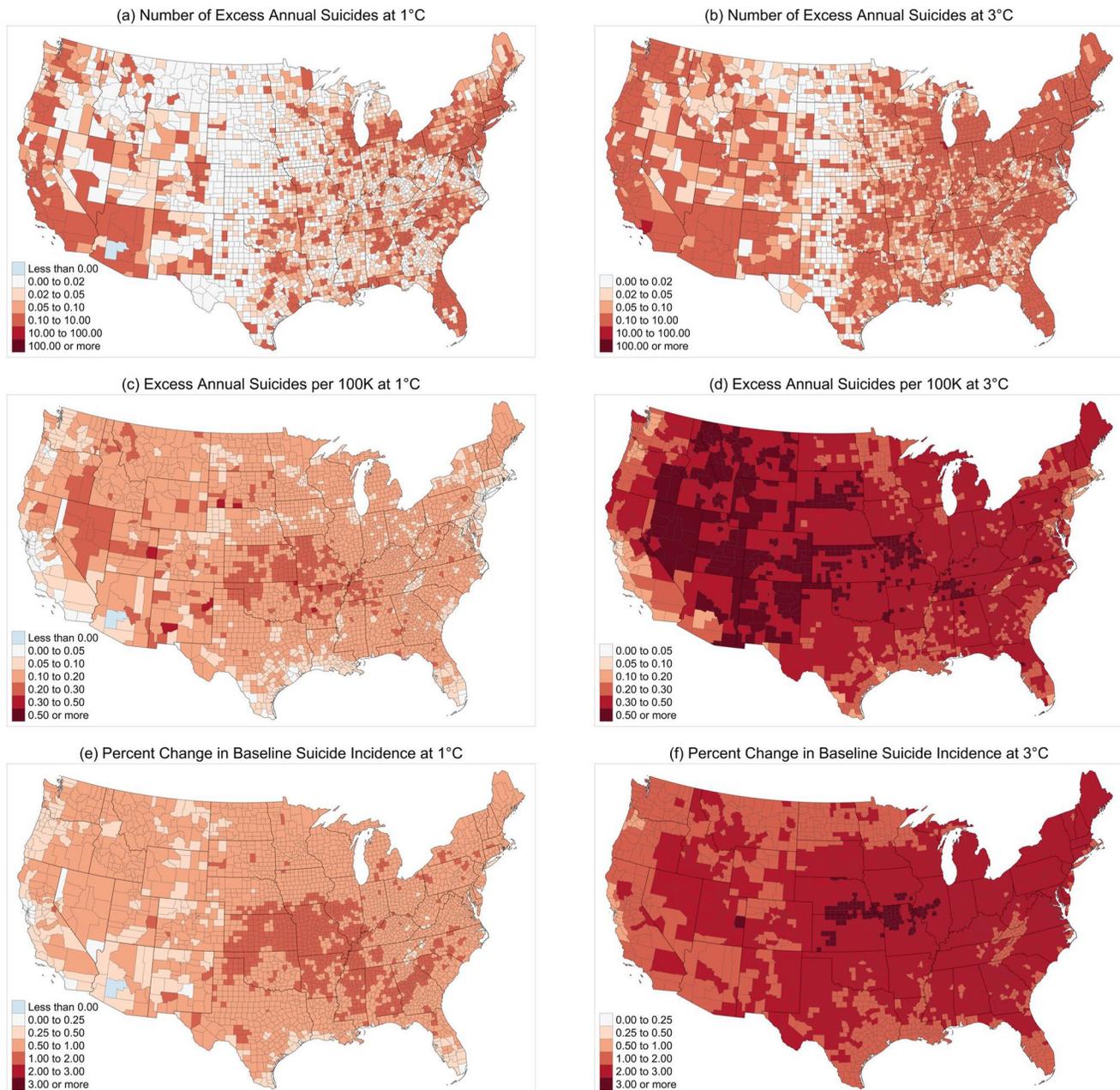
Figure 1. Spatial patterns in the United States (U.S.) climate change-attributable suicide impacts. This figure shows the spatial patterns in the conterminous U.S. of climate change. Panels (a and b) show annual excess number of suicides by county for 1 and 3°C of warming, respectively. Panels (c and d) standardize the spatial patterns with respect to population size and highlight impacts from climate change and baseline suicide rates. Panels (e and f) further normalize the spatial patterns with respect to the baseline suicide rate, revealing that the largest proportional changes in suicide incidence are to be expected in the Midwest, the North Central, the South Central, and the Southeast.

2000–2050. Using a displacement-adjusted linear temperature-suicide relationship, Burke et al. (2018) estimated 14,020 (95% CI: 5,600–26,050) excess suicides due to a temperature increase of 2.5°C (95% range: 1.3–3.7°C) by 2050. This corresponds to 275 excess suicides annually, which is in line with our displacement-adjusted estimates for 1 and 2°C of warming (arrival years generally between 2010 and 2050): 238 (CI 90%: 169–316) and 473 (CI 90%: 339–617) excess annual suicides, respectively.

The climate-suicide impacts reported here should be viewed in light of several limitations. First, ours is a quantitative synthesis study that relies on simulations to evaluate the outcome of interest. We analyze the influence

of several sources of uncertainty and variability on our results, including the GCM and health impact function choice, population size, suicide rates, uncertainty about health impact function parameter values, and VSL. However, there are significant unquantifiable uncertainties about the future contexts in which climate change would occur. For example, we find that our conclusions are sensitive to assumptions about growth in population size and income during 2015–2100. There is also considerable uncertainty associated with the use of model-based gridded high-resolution climate data, particularly in areas that are away from weather stations (Walton & Hall, 2018). Suicide rates, derived from 1999 to 2019 data, are also an important driver of our estimates. to With increased awareness of mental health issues, as well as emerging health and societal changes due to the ongoing COVID-19 pandemic, we expect that historical suicide rates can have their limits when being used to approximate future suicide rates. Furthermore, we do not consider the impact of complex societal changes that may result from changes in the climate system (e.g., via alterations in income levels or political stability) that may also affect future suicide incidence. We assume gradual rates of temperature change throughout the century, rather than those that are accelerated and occur at certain time intervals. The latter would lead to compounded temperature effects, thus making adaptation and mitigation efforts more difficult, but also making resultant effects more difficult to predict. Moreover, we are unaware of any existing models that would allow for the prediction of that type of punctuated equilibrium, accounting for major temperature disruptions. This conceivably could be a limitation, although it is outside of the scope of this study. Another, related conceivable limitation is that, as discussed previously, we rely on the SSP2 pathway, which may lead to undercounting the impacts analyzed herein. While this provides us with a more realistic view of U.S. projections, relative to other pathways, the SSP2 population projections are lower than that reflected in the RCP8.5 temperature projections with SSP2 population projections. Thus, undercounting may occur as higher temperatures projected in the RCP8.5 scenario are driven by greater population sizes.

Second, because our study relies on observed relationships between temperature and incidence, any adaptation mechanisms are represented to the extent they were used in the observed period. The models that we employ in our study design do not evaluate the effects of additional adaptation actions beyond those captured in the empirical data. Thus, they do not consider potential adaptation mechanisms and their impacts that are not otherwise accounted for in the data (e.g., the future availability of and access to air conditioning and mental healthcare, broader policies and programs implemented to address and curtail warming effects, such as cooling shelters or subsidies for air conditioning expenses, etc.). These factors, each with their own costs, presumably will moderate the public health effects of increased temperatures, and potentially mental health effects writ large, by providing vulnerable populations with relief from the heat. We do not account for such adaptation mechanisms for a number of reasons. Chiefly, it is difficult to predict the development and implementation of individual policy measures at any scale, let alone in aggregate; and until such measures are enacted, it is virtually impossible to account for their impact herein. Additionally, existing research does not demonstrate evidence of a significant relationship between adaptation measures and suicides (Burke et al., 2018; Mullins & White, 2019), although this may not hold true for additional mental health effects outside of the scope of this paper, such as anxiety and depressive disorders. Future work may examine more closely the impacts of adaptation measures on the relationships between climate change and suicide or the incidence of other mental health illnesses.

Third, in conducting this research, we determine data gaps that should be noted and that if addressed could open many opportunities for future research. For instance, there is limited research capturing the relationship between climate change and mental health effects other than suicide and BMHDs, from the less-specific (e.g., generalized anxiety or depression) for which individuals may seek limited or no care to those outcomes that require clinical care. Hospitalization studies published to date are not national in scope and therefore do not meet our inclusion criteria (see Section S1 in Supporting Information S1). Furthermore, some outcome measures do not have robust economic valuation studies to support their inclusion (e.g., BMHD). Relatedly, another type of endpoint that should be explored further and projected are the linkages between mental health outcomes and extreme weather events such as hurricanes, tornadoes, or other such occurrences (Bell et al., 2018). The frequency and locations of these events are not possible to predict robustly for future years (Hoegh-Guldberg, 2018; IPCC, 2012); thus, their impact evaluation is not included in this paper, and we recommend additional research into this area.

Finally, a major research gap is how the climate change-mental health or climate change-suicide relationships pertain to sensitive populations and environmental justice and equity. Our paper examines the suicide and climate change relationship among populations stratified by location, age, and sex; however, we are unable to

further categorize results by additional demographics, including socioeconomic status, race (Mason et al., 2020; Williams et al., 2016), gender and sexuality (e.g., LGBTQ+) (Newcomb et al., 2020; Sutter & Perrin, 2016), substance misuse (Chorlton & Smith, 2016; Whiting et al., 2020), rurality to a greater extent than incorporated herein (Breslau et al., 2014; Robinson et al., 2017; West et al., 2013), or other descriptors pertaining to protected classes that may be relevant and are often linked to greater incidences of negative mental health outcomes. Additional information, including that produced by quantitative, qualitative, and mixed-methods studies and impact estimates among stratified populations, is needed to describe disproportionate effects of climate change on mental health and vulnerable groups, in particular, in greater detail. Future work in this area has the potential to contribute to the development of effective mental health interventions in the face of a changing climate.

Conflict of Interest

The views expressed in this article are solely those of the authors and do not necessarily represent those of the U.S. Environmental Protection Agency or the federal government. The authors report real or perceived financial conflicts of interest for any author. Additionally, no author reports any other affiliations that may be perceived as having a conflict of interest with respect to the results of this paper.

Data Availability Statement

Our inputs and results are accessible on the EPA's Environmental Data set Gateway. Our code is available on GitHub and archived on Zenodo (https://doi.org/10.5281/zenodo.6096271) (Belova et al., 2022a). Each file in the Environmental Data set Gateway is accessible under DOI https://doi.org/10.23719/1524370 (Belova et al., 2022b), with a permissive open source license equivalent to the MIT Open Source Initiative. The individual files are available for download at the following individual links. Statistical analyses were conducted using (R Core Team, 2021) R version 4.1.0 (218) Platform: x86_64-apple-darwin17.0 (64-bit), running under macOS Big Sur 11.6.1. The climate, population, and suicide incidence rate data used as modeling inputs in the study are available at https://pasteur.epa.gov/uploads/10.23719/1524370/ccmh-data-inputs.zip (csv files). The valuation data used as modeling inputs in the study are available at https://pasteur.epa.gov/uploads/10.23719/1524370/ccmh-workbooks.zip (workbooks). The central estimates produced by this study are available at https://pasteur.epa.gov/uploads/10.23719/1524370/ccmh-data-results-point.zip. The sampling results for warming degrees 1, 2, and 3°C produced by this study are available at https://pasteur.epa.gov/uploads/10.23719/1524370/ccmh-data-results-sampling-D4D5D6.zip. The sampling results for warming degrees 4, 5, and 6°C produced by this study are available at https://pasteur.epa.gov/uploads/10.23719/1524370/ccmh-data-results-sampling-D1D2D3.zip. The modeling code used to generate results reported in this study is preserved at DOI: https://doi.org/10.23719/1524370 with a permissive open source license equivalent to the MIT Open Source Initiative, and is available for download at https://pasteur.epa.gov/uploads/10.23719/1524370/Projecting-the-Suicide-Burden-of-Climate-Change-in-the-United-States.zip. The live version of the code is openly available at https://github.com/USEPA/projecting-the-suicide-burden-of-climate-change-in-the-united-states.

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