

BMJ Open Mortality of Puerto Ricans in the USA post Hurricane Maria: an interrupted time series analysis

Mario Marazzi,¹ Boriana Miloucheva ,² Gustavo J Bobonis²

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¹Independent Researcher, San Juan, Puerto Rico

²Department of Economics, University of Toronto, Toronto, Ontario, Canada

Correspondence to

Dr Gustavo J Bobonis;
gustavo.bobonis@utoronto.ca

ABSTRACT

Objectives To determine death occurrences of Puerto Ricans on the mainland USA following the arrival of Hurricane Maria in Puerto Rico in September 2017.

Design Cross-sectional study.

Participants Persons of Puerto Rican origin on the mainland USA.

Exposures Hurricane Maria.

Main outcome We use an interrupted time series design to analyse all-cause mortality of Puerto Ricans in the USA following the hurricane. Hispanic origin data from the National Vital Statistics System and from the Public Use Microdata Sample of the American Community Survey are used to estimate monthly origin-specific mortality rates for the period 2012–2018. We estimated log-linear regressions of monthly deaths of persons of Puerto Rican origin by age group, gender, and educational attainment.

Results We found an increase in mortality for persons of Puerto Rican origin during the 6-month period following the hurricane (October 2017 through March 2018), suggesting that deaths among these persons were 3.7% (95% CI 0.025 to 0.049) higher than would have otherwise been expected. In absolute terms, we estimated 514 excess deaths (95% CI 346 to 681) of persons of Puerto Rican origin that occurred on the mainland USA, concentrated in those aged 65 years or older.

Conclusions Our findings suggest an undercounting of previous deaths as a result of the hurricane due to the systematic effects on the displaced and resident populations in the mainland USA. Displaced populations are frequently overlooked in disaster relief and subsequent research. Ignoring these populations provides an incomplete understanding of the damages and loss of life.

INTRODUCTION

Extreme weather events such as hurricanes are growing in frequency and magnitude and are expected to affect a growing population due to migration patterns, ecosystem alteration and climate.^{1 2} The consequences for human lives and the economic costs associated with these disasters are high.^{3 4} While much research documents the direct impacts of natural disasters on the mortality, morbidity, and socioeconomic consequences of populations in affected areas, substantially less attention has been paid to the

STRENGTHS AND LIMITATIONS OF THIS STUDY

- ⇒ One of the first studies to examine excess mortality among migrant and displaced populations following a natural disaster.
- ⇒ Leverage comparison group mortality outcomes to control for seasonality and period-specific effects, minimising potential confounding.
- ⇒ As the mortality outcomes are aggregated at the Hispanic group and gender–age group stratum in each month, we are unable to precisely measure cause-specific mortality.
- ⇒ Our analysis does not allow us to disentangle the excess mortality of displaced populations as opposed to longer-term migrants or second or third-generation individuals of such ancestry.

consequences for populations displaced as a result of these events.^{3 5 6}

While all victims of natural disasters face common challenges, displaced populations undergo distinct experiences that are specific to their relocation—such as additional psychological stressors and disruption in access to healthcare services as well as changes in their living conditions and social networks; see Uscher-Pines and Frankenberg *et al* for systematic reviews of the literatures on the health effects of relocation following disaster and of the demographic consequences of disasters more generally.^{7 8} These circumstances can either compound or mitigate the effects of disasters for these populations. Consistent with the heterogeneity in the populations' experiences, a growing body of research finds mixed evidence regarding the incidence and extent of higher mortality risk among displaced populations. In an early systematic review of the literature, Uscher-Pines documents neither short-term nor long-term consequences on mortality for displaced populations following postdisaster relocation.⁸ Subsequent studies find higher mortality risks for specific displaced subpopulations such as among relocated



institutionalised elderly; see Willoughby *et al* for a systematic review.⁹

However, measuring the mortality consequences of disasters among these populations is inherently challenging due to the displacement that can take place before, during, or in the aftermath of an event. Most data on disasters are obtained from those who remain relatively near the site of the disaster or who have relocated to obvious camps and refugee settlements. The mortality of the rest of the displaced population may be missed if proper attention is not taken in the design of data collection efforts. Furthermore, displacement makes it difficult to know how completely those interviewed represent the underlying population exposed to the event, nor is it possible to benchmark respondents' experiences during and after an event against their circumstances before the event, or against populations that were not exposed to the event but are otherwise similar.^{6 10} Few studies of displaced populations have analysed representative sample data before and after exposure to a disaster relative to comparable populations to be able to credibly measure the effects of these events. Specifically, studies of populations after large-scale disasters typically describe the experiences of particular groups of individuals—such as those displaced to specialised refugee locations—providing little information about individuals who settled elsewhere, although there are exceptions.^{6 7 10–16} In spite of these methodological limitations, this literature has shaped our understanding of mortality patterns among displaced populations. If conclusions about these forms of vulnerability do not transcend specific groups and cannot be replicated more generally, their informativeness in planning for or responding to the needs of at-risk populations—monitoring, assessment, programming of interventions, and the targeting of social safety nets—is compromised.

In this article, we contribute to research on the mortality consequences of extreme environmental hazards among displaced populations in host communities. We conceptualise postdisaster mobility as a coping strategy that occurs along a spectrum from forced displacement to largely voluntary migration.^{6 17–19} Our objective is to estimate the excess mortality experienced by Puerto Ricans in the mainland USA, following the devastation caused in Puerto Rico by Hurricanes Irma and Maria in September 2017. The consensus from existing research documenting excess mortality in the aftermath of the hurricanes—based on death occurrences that happened physically in the archipelago of Puerto Rico—is that well over one thousand people died in Puerto Rico and likely more than three thousand lost their lives (see online supplemental materials table A1).^{20–24} However, to date, no systematic attempt had been made to consider deaths that may have occurred on the mainland USA as a result of this natural disaster. To our knowledge, this is the first study to explicitly examine the postdisaster death occurrences of Puerto Ricans in the mainland USA.

We combine administrative death records data from the US National Vital Statistics System together with population estimates using repeated cross sections of the Public Use Microdata Sample of the American Community Survey (ACS) to estimate monthly immigrant-origin group-specific mortality rates by age, gender, and educational attainment for the period 2012–2018 in the mainland USA. Using these data, which are representative of the at-risk population, we conduct analyses that measure outcomes consistently for individuals from the group affected by the disaster relative to those of comparable populations. We use an interrupted time series difference-in-differences design to examine patterns of all-cause mortality of Puerto Ricans in the USA during the months following the hurricane, using mortality trends for Cuban and Mexican populations in the mainland USA—whose countries of origin or ancestry were not affected by extreme hurricanes that year (or limited population displacement to the USA as a result of these events) and who had historically similar mortality trends preceding the event—as a comparison group.

Identifying the existence and magnitude of a period of excess mortality among Puerto Ricans in the USA in the months following the passage of Hurricane Maria over Puerto Rico would support the hypothesis that displaced and migrant populations also face a higher risk of mortality and possibly other health consequences from exposure to such natural disasters.

METHODS

Data and descriptive statistics

We use publicly available microdata from the National Vital Statistics System of the National Center for Health Statistics to identify deaths of persons of Puerto Rican origin on the mainland USA between 2012 and 2018.²⁵ The data also allow us to identify deaths of persons of other Hispanic origins, which we use as a comparison group. It also includes the month of occurrence, as well as several socioeconomic variables for each death, including the person's age, gender, and educational attainment.

We use the Public Use Microdata Sample of the ACS of the US Census Bureau to estimate the annual population of each Hispanic origin, for each age group, gender, and educational attainment between 2012 and 2018.²⁶ Following Santos-Burgoa *et al*, age was categorised in three groups: 0–39 years, 40–64 years and 65 years or older.²⁰ For age groups 40–64 years and 65 years and older, we also stratified the sample in three groups based on individuals' educational attainment: persons who did not complete high school, those with only a high school degree, and those with some higher education or more.

We employ a standard temporal disaggregation method for time series data based on dynamic models to generate stratum-specific population measures for each month.^{27 28} The technique exploits the time series relationship of the available low-frequency data using a regression model with autocorrelated errors generated by a first-order

autoregressive process. The reference period of the ACS is the 12-month calendar year. As a result, we also restrict the 12-month average population estimate to equal the annual ACS-based population estimate; see online supplemental materials for details.

Because these data are publicly available and deidentified, this study is considered to be research not involving human subjects as defined by US regulation (45 CFR 46.102[d]).

Patient and public involvement

No patients involved.

Statistical analysis

Our empirical strategy consists of an interrupted time series/difference-in-differences design. We compare differences in the gender-by-age group stratum mortality rates of Puerto Ricans before and after September 2017 relative to that of Cubans and Mexicans, comparable Hispanic groups in the USA, during January 2012 to December 2018 time period. In doing so, we effectively use the mortality outcomes of the comparison groups to control for seasonality and period-specific effects. We make these comparisons by gender-by-age group, estimating a system of six (6) linear models of the form:

$$\ln(d_{sgmt}) = \theta_s(\text{Maria}_{mt} \times \text{PR}_{sg}) + \beta_s \ln(\text{Pop}_{sgmt}) + \alpha_{sg} + \gamma_{mt} + \varepsilon_{sgmt}, \quad (1)$$

where d_{sgmt} is the number of deaths of individuals from gender–age group stratum s and Hispanic group g in month m and year t ; Maria_{mt} is an indicator variable for the 6-month period from October 2017 to March 2018; PR_{sg} is an indicator variable for Puerto Rican origin; Pop_{sgmt} is the population level estimate for each Hispanic group g over time; α_{sg} are Hispanic group fixed effects; γ_{mt} are month-by-year fixed effects; and ε_{sgmt} is the error term. This model richly captures seasonality as well as other time trends for each gender-by-age stratum, and accounts for differences in the mortality rate levels between Puerto Ricans and other Hispanic groups. We estimate the models as a system of equations allowing for autocorrelation of the error terms by clustering standard errors at the Hispanic group level.^{29–31} This procedure also allows us to account for the correlation of mortality rates across age groups and gender within each Hispanic group as well as the autocorrelation of mortality for each group, and to generate estimates of aggregate excess mortality for the population based on the stratum-specific models.

We also report a series of estimates from an event study to document the month-specific effects of the Maria shock. Specifically, we estimate equation 2 to explore this:

$$\begin{aligned} \ln(d_{sgmt}) &= \theta_{st} \cdot \mathbf{I}\{g = \text{PR}_g\} \cdot \mathbf{I}\{t = 1, 2, \dots, 6\} \\ &+ \beta_s \ln(\text{Pop}_{sgmt}) + \alpha_{sg} + \gamma_{mt} + \varepsilon_{sgmt} \end{aligned} \quad (2)$$

where $\mathbf{I}\{g = \text{PR}_g\} \cdot \mathbf{I}\{t = 1, 2, \dots, 6\}$ is a vector capturing the interaction of the PR indicator with an indicator variable for each month from October 2017 to March 2018, with September 2017—the month of the event—as the base period. All other variables are as defined above in equation 1. The vector θ_{st} captures the period-specific effects

for each month during the 6-month window described earlier.

Our estimation procedure uses the observed age group-by-gender-specific deaths that occurred over the period of October 2017 until March 2018 as well as our estimated coefficients of the differential change in mortality rates of Puerto Ricans in the mainland USA (θ_s, θ_{st}), to construct estimates of excess mortality for each age group–sex combination and their corresponding 95% CI. We follow an analogous procedure to generate estimates of excess mortality for the population in overall terms. See online supplemental materials for details of the estimation and aggregation procedures.

An important consideration in this analysis is our need to estimate the degree of population displacement of the residents of Puerto Rico to the mainland USA following the hurricanes. We do so by measuring differential changes in population levels for the Puerto Rican population in the mainland USA relative to trends for the comparison groups throughout the period following the hurricanes. This methodology, described in more detail in the online supplemental materials, generates estimates of population displacement, or the population in excess of what would have otherwise been expected. This procedure allows us to both confirm independent estimates of population movements from the territory to the mainland USA during this period and to give confidence to the use of population estimates for the estimation of excess mortality rates.

RESULTS

Overall, 14010 individuals of Puerto Rican background died in the mainland USA between October 2017 and March 2018 (table 1); 7505 (53.6%) were men and 6505 (46.4%) were women (table 2); 9045 (64.6%) were adults aged 65 years or older (table 3). In contrast, between 10866 and 12832 deaths occurred among this population in the 6-month period between October and March in 2012–2013 to 2016–2017 years, the period of observation before the hurricane. We estimated that there were approximately 5.631 million individuals of Puerto Rican origin in the mainland USA in August 2017, and by March 2018, this number was 5.783 million—an increase of approximately 152000 individuals, or a 2.7% population increase (table 1).

We compare mortality outcomes pre and post September 2017 among the Puerto Rican population in the mainland USA relative to other Hispanic groups in the country. In figure 1A, we examine trends in the overall mortality rate of Puerto Ricans in the mainland USA (blue solid line) during January 2012 to December 2018 and that of Cubans and Mexicans (red dashed line) throughout the same period. Between January of 2012 and August 2017, the mortality rate among individuals of Puerto Rican origin averaged 280.89 per 100000. In contrast, the mortality rate among Cubans and Mexicans throughout this period was 232.17 per 100000. In

**Table 1** Excess Mortality of the Puerto Rican population in the mainland USA, overall and by month (October 2017 to March 2018)

	Observed deaths (1)	Δ mortality rate (95% CI) (2)	Population (100 000s) (3)	Expected deaths (4)	Excess deaths (95% CI) (5)	Ratio of observed to expected mortality (95% CI) (6)
Panel A: month-specific estimates						
October 2017	2093	0.022 (−0.006 to 0.051)	56.596	2047	46 (−11.7 to 104.1)	1.02 (0.99 to 1.05)
November 2017	2182	0.059 (0.041 to 0.078)	56.767	2056	126 (87.1 to 164.7)	1.06 (1.04 to 1.08)
December 2017	2551	0.065 (0.048 to 0.082)	56.974	2391	160 (119.4 to 200.7)	1.07 (1.05 to 1.09)
January 2018	2624	0.012 (−0.014 to 0.039)	57.524	2592	32 (−36.1 to 100.5)	1.01 (0.99 to 1.04)
February 2018	2275	0.059 (0.035 to 0.083)	57.708	2145	130 (78.1 to 182.4)	1.06 (1.03 to 1.09)
March 2018	2285	0.004 (−0.008 to 0.016)	57.830	2276	9 (−19.1 to 36.8)	1.00 (0.99 to 1.02)
Panel B: aggregate estimates						
October 2017 to March 2018	14010	0.037 (0.025 to 0.050)	57.233	13496	514 (346.5 to 681.0)	1.04 (1.03 to 1.05)
October 2017 to December 2017	6826	0.037 (0.024 to 0.049)	56.779	6581	245 (163.6 to 326.9)	1.04 (1.02 to 1.05)

Column 1 reports observed deaths of the Puerto Rican population in the mainland USA, and column 3 reports estimates of the overall population of Puerto Ricans in the mainland. Column 2 reports estimates of the difference in the natural logarithm of the mortality of Puerto Ricans relative to Cubans and Mexicans based on the aggregation of estimates from equation 2 (panel A) and equation 1 (panel B) estimated for each gender-by-age group, as well as 95% CIs in parentheses. Columns 4, 5 and 6 respectively report estimates of expected deaths, excess deaths and the ratio of observed to expected deaths calculated from observed deaths (column 1) and estimates of changes in mortality rates (column 2); 95% CIs of the level of excess deaths and of the ratio of observed to expected deaths are reported in parentheses.

spite of this difference in mortality levels, the two groups experienced very similar mortality seasonal patterns and trends in the period up to September 2017, when Puerto Rico was severely affected by Hurricanes Irma and Maria (figure 1A).

Following these events, we observe a modest trend break in the mortality rate of Puerto Ricans relative to that of Cubans and Mexicans, in the 0.08–4.03 deaths per 100 000 range (figure 1B). The figure helps validate the research design. In the online supplemental appendix, we include a series of placebo tests we performed to evaluate whether there are significant increases in mortality of the Puerto Rican population relative to that of the comparison group pre October 2017, which confirm the common trends assumption. Moreover, it reveals the mortality rate gap to be most pronounced during the October 2017 through March 2018; we use this post hurricane 6-month event window to capture estimates of excess mortality for the Puerto Rican population in the mainland USA.

Our results span the 6-month period following the passing of Hurricane Maria (October 2017 to March 2018). We find a statistically significant increase in the mortality rate for persons of Puerto Rican origin during this period of approximately 3.7% (95% CI 2.4% to 4.9%) higher than would have otherwise been expected (see table 1) (The results are robust to restricting the sample to start in later years (ie, 2013, 2014), but with somewhat lower levels of precision.). In absolute terms, this is equivalent to 514 excess deaths (95% CI 346 to 681) of persons of Puerto Rican origin that occurred on the mainland USA.

The month-specific estimates of the excess mortality increase gradually throughout the fourth quarter and peak at 6.5% (95% CI 4.8% to 8.2%) in December 2017 and fluctuate in a downward trajectory during the first quarter of year 2018 (table 1). These month-specific excess mortality rate estimates imply a pattern of excess death, starting just after the hurricanes in October 2017 with 46 excess deaths (95% CI −12 to 104), up to 160

Table 2 Excess mortality of the Puerto Rican population in the mainland USA, by age group and sex (October 2017 to March 2018)

	Observed deaths (1)	Δ mortality rate (95% CI) (2)	Population (100 000s) (3)	Expected deaths (4)	Excess deaths (95% CI) (5)	Ratio of observed to expected mortality (95% CI) (6)
Panel A: 0–39 years of age						
Men	936	–0.023 (–0.026 to –0.019)	18.782	957.6	–22 (–23 to –20)	0.98 (0.98 to 0.98)
Women	433	0.011 (–0.106 to 0.129)	17.635	428.2	5 (–18 to 28)	1.01 (0.96 to 1.07)
Panel B: 40–64 years of age						
Men	2320	–0.005 (–0.016 to 0.005)	7.626	2332.5	–12 (–24 to –1)	0.99 (0.99 to 1.00)
Women	1276	–0.041 (–0.086 to 0.004)	7.967	1329.1	–53 (–80 to –26)	0.96 (0.94 to 0.98)
Panel C: ≥ 65 years of age						
Men	4249	0.073 (0.008 to 0.137)	2.222	3950.9	298 (182 to 414)	1.08 (1.04 to 1.11)
Women	4796	0.064 (0.041 to 0.088)	3.002	4498.0	298 (250 to 346)	1.07 (1.05 to 1.08)
Panel D: all						
Men	7505	0.036 (0.022 to 0.050)	28.630	7241.0	264 (162 to 366)	1.04 (1.02 to 1.05)
Women	6505	0.039 (0.028 to 0.050)	28.604	6255.0	250 (179 to 320)	1.04 (1.03 to 1.05)

Column 1 reports observed deaths of the Puerto Rican population by gender and age group in the mainland USA, and column 3 reports estimates of the overall population of the respective group of Puerto Ricans in the mainland. Column 2 reports estimates of the difference in the natural logarithm of the mortality of Puerto Ricans relative to Cubans and Mexicans based on the aggregation of estimates from equation 1 estimated for each gender-by-age group, as well as 95% CIs in parentheses. Columns 4, 5 and 6 respectively report estimates of expected deaths, excess deaths and the ratio of observed to expected deaths calculated from observed deaths (column 1) and estimates of changes in mortality rates (column 2); 95% CIs of the level of excess deaths and of the ratio of observed to expected deaths are reported in parentheses.

(95% CI 119 to 201) in December 2017 and 9 (95% CI –19 to 37) in March 2018.

Table 2 reports estimates of excess mortality by age group and gender. Among the population aged 65 years or older, mortality was higher than the expected pattern for this population throughout the October 2017 to March 2018 period: 7.3% (95% CI 0.8% to 13.7%) for men and 6.4% (95% CI 4.1% to 8.8%) for women. This is equivalent to 298 excess deaths for men (95% CI 182 to 414) and the same amount for women (95% CI 250 to 346). When examining excess mortality by cause of death among this age group, we estimate these to be concentrated in deaths related to heart diseases, cancer and diabetes; see online supplemental materials for details.

We find no robust evidence of differences in mortality from the expected pattern for the younger age population throughout this period. The empirical models suggest mortality decreased marginally by 0.5% (95% CI

–0.5% to 1.6%) and 4.1% (95% CI 0.4% to 8.6%) among, respectively, men and women aged 40–64 years and by 2.3% (95% CI 1.9% to 2.6%) among men aged 0–39 years.

The point estimates in **table 3** suggest that populations from all educational levels were affected, but excess deaths were more evident in certain groups. For example, we found 243 excess deaths (95% CI 154 to 332) occurred among old age women with less than high school, 175 excess deaths (95% CI 127 to 223) among old age men with a high school diploma, and 61 (95% CI 39 to 83) and 102 (95% CI 89 to 114) excess deaths among old age men and women respectively with at least some higher education. We exclude deaths and population counts with missing educational attainment data from this particular analysis. Accordingly, excess mortality estimates for the group of individuals aged 65+ in **table 3** do not sum to the estimates reported in panel C of **table 2**. Nevertheless, given the level of precision

Table 3 Excess mortality of the Puerto Rican population ages 65 and older in the mainland USA, by education group and sex (October 2017 to March 2018)

	Observed deaths (1)	Δ mortality rate (95% CI) (2)	Population (100 000's) (3)	Expected deaths (4)	Excess deaths (95% CI) (5)	Ratio of observed to expected mortality (95% CI) (6)
Panel A: 65+ years of age, high school dropouts						
Men	1802	0.121 (−0.110 to 0.352)	0.911	1597	205 (37 to 373)	1.13 (1.01 to 1.25)
Women	2232	0.115 (0.017 to 0.214)	1.168	1989	243 (154 to 332)	1.12 (1.07 to 1.17)
Panel B: 65+ years of age, high school graduates						
Men	1560	0.119 (0.044 to 0.195)	0.591	1385	175 (127 to 223)	1.13 (1.09 to 1.17)
Women	1565	0.012 (−0.033 to 0.058)	0.884	1546	19 (−13 to 51)	1.01 (0.99 to 1.03)
Panel C: 65+ years of age, some college or more						
Men	774	0.082 (0.015 to 0.150)	0.700	712.8	61 (39 to 83)	1.09 (1.05 to 1.12)
Women	896	0.121 (0.087 to 0.155)	0.929	794.2	102 (89 to 114)	1.13 (1.11 to 1.15)

Column 1 reports observed deaths of the Puerto Rican population by gender, age and education group in the mainland USA, and column 3 reports estimates of the overall population of the respective group of Puerto Ricans in the mainland. Column 2 reports estimates of the difference in the natural logarithm of the mortality of Puerto Ricans relative to Cubans and Mexicans based on the aggregation of estimates from equation 1 estimated for each gender-by-age-by-education group, as well as 95% CIs in parentheses. Columns 4, 5 and 6 respectively report estimates of expected deaths, excess deaths and the ratio of observed to expected deaths calculated from observed deaths (column 1) and estimates of changes in mortality rates (column 2); 95% CIs of the level of excess deaths and of the ratio of observed to expected deaths are reported in parentheses.

of our estimates, we cannot reject that these are in the same range.

DISCUSSION

Main findings

Our study documents an increase in mortality for persons of Puerto Rican origin in the mainland USA during the 6-month period following Hurricane Maria (October 2017 through March 2018). Our findings indicate that measures of excess mortality based on death occurrences in Puerto Rico following the hurricane may be underestimating total excess mortality by an additional 514 deaths (95% CI 346 to 681) in the 6 months following the event, partly due to significant displacement of the Puerto Rican population to the mainland USA. Crucially, this increase in mortality was concentrated among the most vulnerable populations, with old age adults with lower levels of education seeing the largest increases. These patterns are consistent with excess mortality estimates obtained in Puerto Rico.^{23 24} Analyses of these data also provide a rich description of heterogeneity of the event's impacts to yield generalisable knowledge.

Contribution, limitations and relationship to the literature

The study contributes to the literature documenting the mortality consequences of Hurricane Maria in Puerto Rico. Several previous attempts to estimate the mortality effects of Hurricane Maria in Puerto Rico, including the official death toll estimate prepared by the Government of Puerto Rico,

used Puerto Rico death registrar data and previous years' mortality rate estimates as a benchmark to identify periods of excess mortality in Puerto Rico.^{20–24} Preferred mortality estimates for the 6-month and 7-month period following the disaster—which considered only deaths registered in Puerto Rico despite significant population displacement and excluding deaths among the population displaced to the mainland—were as high as 2975 and 3400, respectively.^{20 23} We present a summary of the data, techniques and treatment periods employed in this research in the online supplemental file 1. This focus on deaths occurring in the territory resulted in an underestimation of the death toll by approximately 14.7%, which we estimate occurred in the USA. In contrast, Kishore *et al* (2018) surveyed a representative sample of households, asking survivors to account for the whereabouts of all people who lived in their community prior to the hurricane irrespective of the location of the occurrences of death among community members (on the island or elsewhere).³² Accordingly, they found a mortality rate that yielded an estimate of 4645 excess deaths (95% CI 793 to 8498) on account of Hurricane Maria. Our finding of excess mortality among the population of Puerto Rican origin in the mainland USA contributes to explaining the difference in estimates from these two methodological approaches.

An additional contribution of the study is the use of a research design to credibly estimate the excess mortality of displaced and migrant populations during this period, while carefully accounting for population displacement following

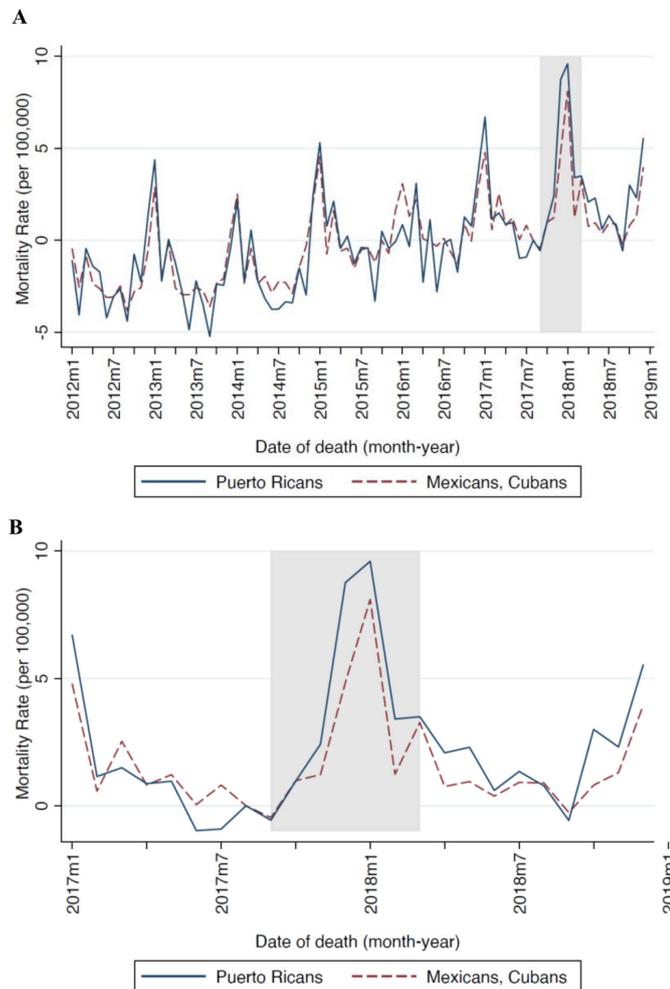


Figure 1 Standardised monthly mortality from January 2012 to December 2018 (A) and from July 2017 to December 2018 (B). August 2017 is used as the standard mortality rate for both populations.

the disaster. Using comparator populations of Cubans and Mexicans in the mainland USA, our design robustly accounts for different population and mortality trends by age group and gender to account for both displacement and differential mortality among the Puerto Rican population. Our estimates of displacement of the population ages 65 and older of approximately 7.1% (40 700 individuals) is in line with the existing literature and supports the consensus using other methodologies that the natural disaster led to displacement in aggregate terms of approximately 4.1%–5.6% of the total population of Puerto Rico.^{33 34} This design, effectively used in related studies and other contexts to account for population movements, is broadly applicable both in other countries and in other disaster contexts (both natural and otherwise), particularly as displacement and mobility becomes an increasingly important feature of natural disasters.¹¹

Our study is informative regarding the broad mortality consequences of the disaster among the displaced and migrant population of Puerto Ricans in the USA. This measure, however, limits our ability to quantify the elevated burden of disease from morbidity and disability among this population. We also face some limitations in our ability to

precisely estimate cause-specific mortality or the causal pathways for such trends. Given the relatively small numbers of deaths in the population in the period under observation (monthly range 2119–2862), generating informative estimates of more finely defined cause-specific mortality is not feasible.

Finally, because we use the deaths of persons who are identified as Puerto Rican in their death certificate, our analysis does not allow us to disentangle the excess mortality of displaced populations as opposed to longer-term migrants or second or third-generation individuals of such ancestry. Information on the deaths of Puerto Rico residents in the continental USA may be incomplete and/or prone to undercounting if the Puerto Rico residency status of such individuals is under-reported on death certificates. This phenomenon is particularly exacerbated among vulnerable, geographically mobile, migrant populations (Our estimate also excludes persons exposed to the hurricane, who may have been displaced to other countries, most notably the neighbouring Dominican Republic. While not directly exposed, it is possible that longer-term migrants may have been psychologically or economically affected by the events in the aftermath of Hurricane Maria, which may also have affected their mortality risk. At the same time, this approach excludes from the analysis individuals who are not of Puerto Rican origin but who nevertheless may have been in Puerto Rico at the time of hurricane, and who may have been displaced in the aftermath of Hurricane Maria.). Nonetheless, the fact our estimated effects are concentrated among vulnerable populations—consistent with the excess mortality estimates obtained for death occurrences in Puerto Rico—supports the view that we mainly capture excess deaths among the sizeable population that was displaced to the mainland USA following the natural disaster. Future research could undertake epidemiological studies with microlevel data to precisely estimate cause-specific mortality, the causal pathways for such patterns, as well as mortality estimates that include all hurricane-related deaths according to Centers for Disease Control and Prevention (CDC) guidelines for death occurrences in Puerto Rico and in the continental USA.

Policy implications

Our study emphasises the importance of considering displaced populations in the calculation of postdisaster excess mortality. These populations may suffer from relative inattention in the context of both needs assessment and disaster relief, and we argue that overlooking these provide an incomplete understanding of the magnitude of the health consequences of natural disasters.

This analysis suggests the need for not only equitable disaster preparedness but also the importance of cross-jurisdiction data sharing.²⁰ These already vulnerable populations may face a number of additional hurdles on relocation, such as healthcare disruptions and psychological stressors, which may exacerbate health impacts of the disaster. Receiving jurisdictions would, thus, benefit from an improved understanding of both the dynamics of postdisaster displacement and its consequences.

Already important efforts exist among jurisdictions in the USA, such as the State and Territorial Exchange of Vital Events of the National Association for Public Health Statistics Information Systems, to facilitate vital records for use by other state-level and territorial public health organisations. However, more coordination is required to speed the flow of data to gain a more comprehensive understanding of the scale of disasters in other countries. Moreover, even among jurisdictions within the USA, this process can take a considerable amount of time. The speed of flow of vital records depends on the effectiveness of local and county vital registrars to share this information. Ensuring timely exchange of death records among jurisdictions would ensure disaster death toll estimates based on vital records are complete, and would hence allow public authorities to have a comprehensive understanding of the scale of the disaster in a timely fashion.

Contributors MM: conceptualisation, data curation, supervision, validation, visualisation, writing—original draft and writing—review & editing. BM: conceptualisation, data curation, formal analysis, investigation, methodology, visualisation, writing—original draft and writing—review & editing. GJB: conceptualisation, formal analysis, investigation, methodology, project administration, supervision, validation, visualisation, writing—original draft and writing—review & editing, guarantor for the final manuscript.

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ORCID iD

Boriana Miloucheva <http://orcid.org/0000-0002-8183-137X>

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Supplementary Materials

A. Additional Figures and Tables

Table A1. Existing Excess Mortality Estimates of Hurricane Maria¹⁻⁵

Reference	Main Data Source	Pre-Exposure Period	Exposure Time Period	Estimation Methodology / Design	Preferred Excess Mortality Estimate [95% CI]
Acosta R, Irizarry R. (2018)	Vital records of death occurrences in Puerto Rico	1/1/1985 – 9/20/2017	9/21/2017 – 4/15/2018	Excess mortality	3,400 ± 300
Kishore N. et al. (2018)	Representative, stratified sample household survey	9/20/2016 – 12/31/2016	9/20/2017 – 12/31/2017	Aggregation of mortality reports	4,645 ± 3,852
Santos-Burgoa C. et al. (2018)	Vital records of death occurrences in Puerto Rico	7/1/2010 – 8/31/2017	9/1/2017 – 2/28/2018	Excess mortality	2,975 ± 317
Santos-Lozada A, Howard JT (2018)	Vital records of death occurrences in Puerto Rico	1/1/2010 – 8/31/2017	9/1/2017 – 11/31/2017	Excess mortality	1,139 ± 133
Cruz-Cano R, Mead E (2019)	Vital records of death occurrences in Puerto Rico	1/1/2008 – 8/31/2017	9/1/2017 – 10/31/2017	Excess mortality	1,205 ± 498
Rivera, R., Rolke W. (2019)	Vital records of death occurrences in Puerto Rico	1/1/2015 – 9/19/2017	9/20/2017 – 12/31/2017	Excess mortality	1,318 ± 249

Notes: Column 2 reports the main data source used to perform the analysis. Columns 3 and 4 respectively report the period used as a benchmark to identify excess mortality before the Hurricane and the period post-Hurricane during which the period of excess mortality is estimated. Column 5 summarizes the empirical methodology, and column 6 reports the preferred excess mortality estimate and 95% confidence interval.

B. Methods

B.1. Temporal Disaggregation of Population Estimates

Annual population estimates of Puerto Ricans, Mexicans and Cubans in the United States were disaggregated to a monthly frequency using the Chow-Lin maxlog method.^{6,7} This standard method of temporal disaggregation derives the high-frequency (monthly) data from low frequency (annual) data, allowing for the use of related high-frequency data which the researcher has reason to believe is related to the target time series. In applying this method, the researcher is able to create a high frequency dataset consistent with the initial low-frequency data, but which incorporates the short-term volatility of the related high-frequency data.¹ This is done through a standard least-squares estimation, where the error term is assumed to follow an AR(1) process. In our disaggregation, we chose not to impose a particular short-term volatility, and so regress our low-frequency data for each age-sex-education-Hispanic strata on a constant term, with a mean conversion.

¹ https://ec.europa.eu/eurostat/cros/content/chow-lin-method-temporal-disaggregation-method_en

B.2. Estimation of Excess Mortality Levels – Overall Population and by Subgroup

Our estimation procedure uses the observed age-group-by-gender specific deaths that occurred over the period of October 2018 until March 2018 as well as our estimated coefficients of the differential change in mortality rates of Puerto Ricans in the mainland US (θ_s and θ_{st}), to construct estimates of excess mortality for each age-group-gender combination and their corresponding 95 percent confidence interval. To do this:

1. We first obtain the estimates of θ_s and θ_{st} separately for each age-group-gender combination.
2. We then estimate expected deaths following Maria for each of these subgroups using a non-linear combination of our estimates of the change in mortality rates and the observed deaths. Using nonlinear estimation, we estimate the expected deaths of an age-group-gender combination to be equal to $\exp(\ln(\text{Observed Deaths}_s) - \theta_s)$. This is also performed using the period-specific effects (θ_{st}) and observed deaths. This nonlinear estimation procedure also produces standard errors, which are used to construct confidence intervals.
3. We estimate excess deaths by subtracting the expected deaths estimated in (2) from the observed mortality rates for each age-group-gender combination.
4. Finally, to construct the ratio of observed to expected mortality we divide the observed deaths for each age-group-gender combination by our estimate of expected mortality in (2).

To aggregate our age-group-by-gender results to the overall population, we follow a similar procedure:

1. Estimate, as before, our main specification, to obtain a θ_s for each of the three age-groups.
2. Aggregate the age group-gender-specific observed deaths to measures at the desired level of aggregation.
3. We then estimate expected deaths following Maria for each of these subgroups using a non-linear combination of our estimates of the change in mortality rates and the observed deaths. Using nonlinear estimation, we calculate, more specifically, the expected deaths of the group, h , combination to be equal to $\sum_h \exp(\ln(\text{Observed Deaths}_h) - \theta_{sh})$. This nonlinear estimation procedure also generates standard errors, which are used to construct confidence intervals.
4. Estimate the implied excess deaths by subtracting the expected deaths in (2) from the observed deaths for each age-group: $\sum_h (\text{Observed Deaths}_h) - \sum_h \exp(\ln(\text{Observed Deaths}_h) - \theta_{sh})$.
5. Construct the ratio of observed to expected mortality using the aggregated observed deaths from (2) and the estimated aggregate expected deaths from (3).

B.3. Estimation of Population Displacement – Overall and by Subgroup

An important consideration in this analysis is our need to estimate the degree of population displacement of the residents of Puerto Rico to the mainland U.S. following the hurricanes. We do so by measuring differential changes in population levels for the Puerto Rican population in the mainland U.S. relative to trends for the comparison groups throughout the period following the Hurricanes.

Again, we make these comparisons by gender and age group, and estimate a system of linear models of the form:

$$\ln(\text{Pop}_{sgmt}) = \tau_s(\text{Maria}_{mt} \times \text{PR}_{sg}) + \mu_{sg} + \delta_{mt} + v_{sgmt}, \quad (\text{B1})$$

where the main outcome and explanatory variables as defined above; μ_{sg} are Hispanic group fixed effects; δ_{mt} are month-by-year fixed effects; and v_{sgmt} is the error term; we employ the same estimation procedure. We follow an analogous estimation and aggregation procedure to generate estimates of group-specific and aggregate levels of population displacement in the six-month period following the Hurricane (see Appendix B2 for details). This procedure allows us to both confirm independent estimates of population movements from the territory to the mainland U.S. during this period and to give confidence to the use of population estimates for the estimation of excess mortality rates.

Population displacement was concentrated among the population of individuals ages 65 and older (Table B.1). The population for this group was higher than the expected pattern throughout the October 2017-March 2018 period: the point estimates imply a population increase of 6.0 percent among men (95% CI 1.02 – 1.11) and of 9.7 percent among women (95% CI 1.04 – 1.17) for women. In terms of the temporal pattern, we detect increases in population levels of 2.5 and 14.6 percent among both older age women and men starting in November 2017 until March 2018, with

consistently greater statistical precision among the former group.² In contrast, we find no robust evidence of increases in population from the expected pattern for the younger age populations throughout this period. These estimates are consistent with existing evidence that a large share of the post-disaster displacement among the Puerto Rico-based population occurred among the elderly.²

Table A2. Existing Displacement Estimates of Hurricane Maria⁸⁻¹³

Reference	Data source	Treatment Period	Preferred Displacement Estimate
Meléndez and Hinojosa (2017)	American Community Survey	2017-2019	470,335 (14%)
Echenique and Melgar (2018)	Mobile Phone	10/2017 – 02/2018	400,000 (6%)
Alexander, Polimis, and Zagheni (2019)	Facebook, American Community Survey	10/2017 – 01/2018	185,200 (17%)
Santos-Lozada (2019)	Census, Air Travel	2017	154,575
United States Census Bureau (2019)	American Community Survey, Puerto Rico Community Survey	2017 – 2018	142,000 (4.4%)
Acosta et al. (2020)	American/Puerto Rico Community Survey	07/2017-07/2018	129,848 (4%)
	Air Travel	07/2017-07/2018	168,295 (5%)
	Mobile Phone	07/2017-05/2018	235,375 (8%)
	Social Media	08/2017-08/2018	475,779 (17%)

Notes: Column 2 reports the main data sources used to estimate displacement effects of Hurricane Maria. The primary treatment period of each paper is indicated in column 3. Column 4 provides the preferred displacement estimate (with the percent change in parentheses).

Table A2 provides a summary of existing displacement estimates from Hurricane Maria. The patterns we document are largely consistent with the remainder of the literature, although with notable exceptions. One reason for these underlying differences is the source(s) of data used in the analysis. For example, Alexander, Polimis and Zagheni (2019), find a 17% increase in the number of Puerto Rican migrants combining Facebook and American Community Survey data. While the magnitude of this estimate is greater than ours, it is consistent with estimates from Acosta et al. (2020) which similarly use social media data and estimate a 17% change in displacement.³ These social media data have the advantage of providing estimates of population at a time granularity finer than 1-year (as in the case of the ACS and PRCS). One limitation of this type of data, however, is the under-representation or exclusion of older individuals. While Alexander, Polimis and Zagheni (2019) find that changes in population were disproportionately driven by those age 15-30, their analysis does not include individuals over the age of 60. Our estimates suggest that this is an important subpopulation to consider when estimating displacement.

Nevertheless, Acosta et al. (2020) document that using the ACS data generates the smallest estimates of population displacement, with airline passenger and mobile phone data generating larger displacement at a finer time granularity. Finally, data from Facebook shows the largest declines (475,779 – approximately 17%) in population in Puerto Rico

² Results available upon request from corresponding author.

³ These estimates are similar in magnitude to population projections made by Meléndez and Hinojosa (2017), although are substantially larger than estimates using ACS data from the United States Census Bureau (2019), which estimates only 142,000 Puerto Ricans were displaced.

following the hurricane. Similar estimates are provided in Echenique and Melgar (2018), who use mobile phone tracking data to understand population dynamics. While they provide rich information on the destination of these displaced individuals, little is known about their demographic characteristics.

B.4. Evaluation of Research Design – Placebo Tests of Pre-Event Differential Trends in Mortality

In our interrupted time series / differences-in-differences design, we can test whether there were differences in the trends in mortality rates between the population of Puerto Rican vs. Mexican/Cuban population prior to the hurricanes which occurred in September 2017.

We implement a series of placebo tests to evaluate whether there are significant increases in mortality of the Puerto Rican population relative to that of the comparison group. We drop all data from the period September 2017 onwards, and then create 6-month treatment windows for each period on our sample to mirror our main analysis. We generate 68 placebo differences-in-differences estimates (for event windows starting in January 2012 until August 2018).

We compare our true estimate of the change in the mortality rate coefficients θ_s to the other placebo estimates obtained, reporting the percentile rank of the coefficient from the permutation test as well as the approximate p-value. In addition, we show histograms of the distribution of placebo-based results (see Figure B.1). We conduct this procedure both for the overall population (Panel A) as well as for individuals ages 65 and older (Panel B).

The true estimate of θ_s ($= 0.03732$) for the period October 2017 – March 2018 is ranked first in the distribution of placebo estimates. Specific placebo estimates for the period Oct. 2013-Mar. 2014, Oct. 2014-Mar. 2015, and Oct. 2015-Mar. 2016, and Oct. 2016-Mar. 2017 are -0.0117 , 0.0263 , -0.0113 , and 0.0325 , respectively. For the population of adults aged 65 and over, the true estimate of θ_s ($= 0.0682$) is similarly ranked first in the distribution of placebo estimates, and the distribution of placebo estimates is centered around zero.⁴ Overall, this analysis supports the assessment that there are common mortality trends across the two groups before the event, and that a significant deviation takes place in a pronounced manner in the six-month window following these events.

B.5. Estimation of Excess Mortality Levels by Cause of Death

We estimate models of mortality by main cause of death following the hurricanes in order to evaluate possible pathways connecting the observed excess mortality to the natural disaster. We estimate sets of models as in equation (1) using the natural logarithm of death counts by category as dependent variables, and follow the same procedure described in Section B.1 above to generate aggregate estimates of excess mortality by cause of death. We group causes of death into ten (10) main underlying categories using the NCHS 39-group recode of the ICD 10 Classifications: heart disease (20-26), cancer (5-15), other diseases (37), external (38-42), liver/kidney related (29-31), respiratory (27-28), diabetes (16), and Tuberculosis/Syphilis/HIV (1-3). We conduct this analysis both for the overall population as well as for individuals ages 65 and older (see Table B.2).

Excess mortality was concentrated in deaths related to heart disease: the point estimates imply a ratio of observed to expected deaths of 1.06 among the overall population (95% CI 1.04 – 1.08) and of 1.11 among the adults ages 65 years and older (95% CI 1.07 – 1.14). In overall terms, we also estimate an increase in deaths due to diabetes and external factors; the ratio of observed to expected deaths are respectively 1.03 (95% CI 1.01 – 1.04) and 1.10 (95% CI 1.06 – 1.14). Among the old age population, the point estimates of the ratio of observed to expected deaths suggest increases in cancer (1.05 (95% CI 1.03 – 1.08)), diabetes (1.09 (95% CI 1.08 – 1.09)), and mortality related to other conditions (1.09 (95% CI 1.05 – 1.13)). Changes in mortality rates related to renal and respiratory conditions are positive but not significant at conventional confidence levels. These patterns are consistent with the distinct experiences that are specific to relocation among displaced populations such as additional psychological stressors and disruption in access to healthcare services as well as changes in their living conditions and social networks.^{18,19}

⁴ Table 2 reports estimates of 0.073 and 0.064 for men and women ages 65 and over. The estimate for the population ages 65 and over of both genders is $\theta_s = 0.0682$.

Table B.1: Estimates of Displacement of Puerto Rican Population to the Mainland US, by Age Group and Sex (October 2017 – March 2018)

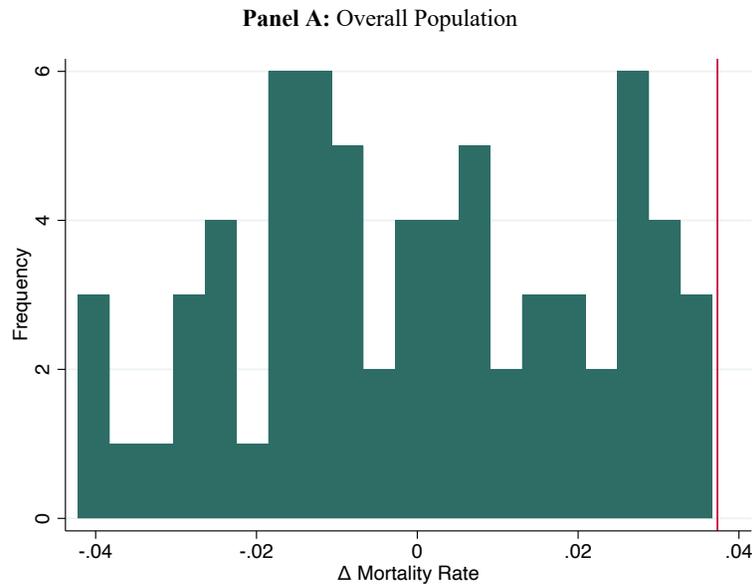
	$\Delta \ln(\text{Population})$ [95% CI]	Population (100,000's)	Expected Pop.	Excess Pop [95% CI]	Ratio of Observed to Expected Pop. [95% CI]
	(1)	(2)	(3)	(4)	(5)
Panel A: 0-39 Years of Age					
Men	0.000 (-0.218, 0.218)	18.782	18.783	-0.001 (-1.869, 1.868)	1.00 (0.90, 1.10)
Women	-0.031 (-0.239, 0.178)	17.635	18.189	-0.554 (-2.282, 1.174)	0.97 (0.87, 1.06)
Panel B: 40-64 Years of Age					
Men	0.000 (-0.061, 0.061)	7.626	7.625	0.001 (-0.211, 0.213)	1.00 (0.97, 1.03)
Women	-0.004 (-0.024, 0.016)	7.967	8.000	-0.033 (-0.107, 0.042)	1.00 (0.99, 1.01)
Panel C: ≥ 65 Years of Age					
Men	0.060 (-0.037, 0.157)	2.222	2.092	0.130 (0.037, 0.222)	1.06 (1.02, 1.11)
Women	0.097 (-0.037, 0.231)	3.002	2.275	0.277 (0.111, 0.443)	1.10 (1.04, 1.17)
Panel D: All					
Men	0.005 (-0.052, 0.061)	28.630	28.500	0.130 (-1.482, 1.742)	1.01 (0.95, 1.06)
Women	-0.011 (-0.057, .035)	28.604	28.913	-0.309 (-1.636, 1.017)	0.99 (.94, 1.04)

Notes: Column 1 reports estimates of the difference in the natural logarithm of the population of Puerto Ricans relative to Cubans and Mexicans in the mainland U.S. based on the aggregation of OLS estimates from equation 1 estimated for each gender-by-age group, as well as 95 percent confidence intervals in parentheses. Column 2 reports estimates of the overall population of Puerto Ricans in the mainland by gender and age group. Columns 3, 4, and 5 respectively report estimates of expected population, excess population (displacement), and the ratio of observed to expected population calculated from the estimated population (col. 2) and estimates of the relative change in population (col. 1); 95 percent confidence intervals of the level of excess population (displacement) and of the ratio of observed to expected population are reported in parentheses.

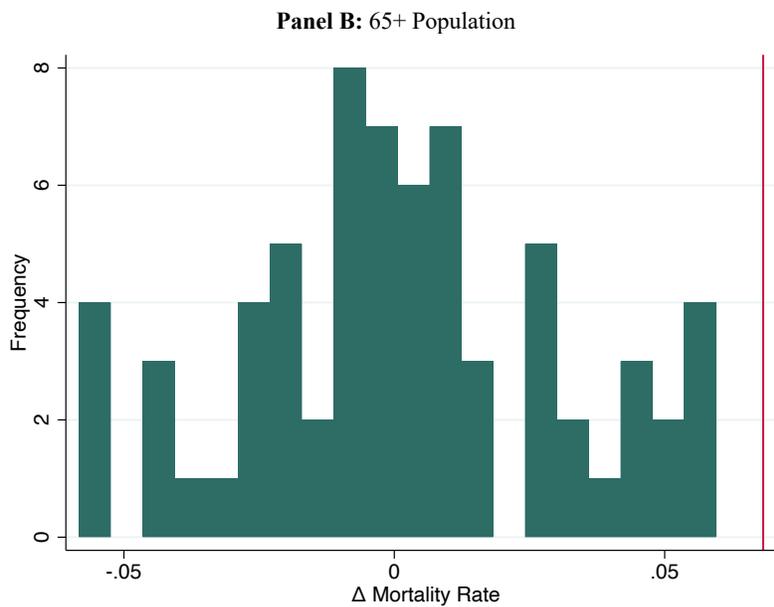
Table B.2: Excess Mortality of the Puerto Rican Population in the Mainland US by Cause of Death, Overall and Old-Age Population (October 2017 – March 2018)

	Observed Deaths (1)	Excess Deaths [95% CI] (2)	Ratio of Observed to Expected Mortality [95% CI] (3)		Observed Deaths (1)	Excess Deaths [95% CI] (2)	Ratio of Observed to Expected Mortality [95% CI] (3)
Panel A: All				Panel B: ≥ 65 Years of Age			
Heart Disease	3,980	223	1.06 (1.04, 1.08)	Heart Disease	3,086	297	1.11 (1.07, 1.14)
Cancer	2,488	29	1.01 (1.00, 1.02)	Cancer	1,624	80	1.05 (1.03, 1.08)
Other	2,577	-1	1.00 (0.94, 1.06)	Other	1,853	154	1.09 (1.05, 1.13)
External	1,627	143	1.10 (1.06, 1.14)	External	282	39	1.21 (1.05, 1.37)
Liver/Kidney	535	-48	0.92 (0.90, 0.94)	Liver/Kidney	301	28	1.10 (0.91, 1.30)
Respiratory	837	15	1.02 (0.84, 1.20)	Respiratory	661	76	1.13 (0.93, 1.33)
Diabetes	601	15	1.03 (1.01, 1.04)	Diabetes	402	32	1.09 (1.08, 1.09)
TB/Syphilis/HIV	118	-1	1.00 (0.92, 1.07)	TB/Syphilis/HIV	49	6	1.14 (1.13, 1.15)

Notes: Column 1 reports observed mortality by cause of death of the Puerto Rican population, overall (left panel) and for those 65 years and older (right panel), in the mainland U.S. Columns 2 and 3 respectively report estimates of excess deaths and the ratio of observed to expected deaths calculated from observed deaths (col. 1) and estimates of changes in mortality rates by cause of death based on equation 1; 95 percent confidence intervals of the level of the ratio of observed to expected deaths are reported in parentheses.

Figure B.1: Distribution of Placebo Tests for Evaluation of Differences-in-Differences Research Design

Notes: Distribution of placebo effects on the change in the natural logarithm of deaths among Puerto Ricans relative to Cubans and Mexicans in the mainland U.S. (comparable to true estimate in Table 1, Panel B: $\theta_s = 0.03732$ indicated by the red vertical line).



Notes: Distribution of placebo effects on the change in the natural logarithm of deaths among Puerto Ricans relative to Cubans and Mexicans in the mainland U.S. age 65+ (comparable to true estimate $\theta_s = 0.0682$ indicated by the red vertical line).

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