Widowhood and Depression Across European Countries: the Moderating Role of Particulate Matter

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Abstract

The negative impacts of stressful life events and air pollution on mental health have been documented separately in distinct literatures. However, few studies take an interdisciplinary approach to assess the potential interaction between stressful life events and air pollution on mental health resulting from similar stress response mechanisms. I consider to what extent air pollution moderates the mental health consequences of one stressful life event, widowhood, for depressive symptoms across European countries. I apply data from the Survey of Health, Aging and Retirement in Europe- Environment (SHARE-ENV), which includes information on respondent's environments, to mixed effects regressions. I find that widowhood is associated with an increase in depressive symptoms, while air pollution yields weaker direct effects. However, I find that air pollution aggravates depressive symptoms following widowhood. This finding suggests that life events should be considered alongside more commonly included time-invariant sociodemographic moderators concerning air pollution and mental health outcomes.

1. Introduction

Separate research streams have explored the consequences of stressful life events and air pollution on mental health outcomes. Despite these hazards triggering similar activation of the hypothalamic-pituitary-adrenal (HPA) axis, a neuroendocrine system responsible for regulating stress, and that individuals might reasonably be exposed to both stressors at the same time, very little is known about the interactions between the two (Snow et al. 2018; Hopf. et al. 2020). In this analysis, I consider the life event of widowhood for two reasons. The first reason is the *severity* of adverse mental health outcomes associated with widowhood. A large body of social scientific literature has established that widowhood is associated with significant risks to mental health, with the development of depression as one of the most common outcomes considered (Stroebe and Schut, 1999; Kristiansen et al. 2019). The second reason is the *commonality* of widowhood as a life event, both across countries, and across populations within countries. Across all EU countries, approximately 6.7 percent of the population is widowed (Eurostat, 2021). Moreover, I focus on widowhood specifically among older adults for several reasons. First is the prevalence of widowhood in this portion of the population: 20 percent of all adults between the ages of 65 and 80 identified as widowed (Eurostat, 2021). Second, depressive disorders within older adults are both prevalent and a significant risk to healthy aging, elevating risks to dementia (Elser et al. 2023), suicide in later life (De Leo, 2022), and disrupting treatment adherence to other morbidities (Schönenberg et al, 2024). The development of population aging across many countries, especially the case in the European context, heightens the importance of understanding what factors may attenuate adverse mental health outcomes associated with common life stressors among this group.

While the risks of particulate matter to respiratory and cardiovascular health have been well documented, a growing literature in environmental epidemiology and neuroscience has established that particulate matter is associated with significant risks to mental health (for a systematic review concerning older adults specifically, see Cativiela-Campos et al. 2025). While the micro-mechanisms through which particulate matter comes to affect mental health are under an active state of literature, there is a consistent finding that particulate matter and other pollutants are introduced to the body via the nasal cavity or lungs, and thereafter provoke a stress response (including elevated levels of cortisol and inflammation). Indeed, this stress response involving a rise in cortisol has also been evoked by literature seeking to understand why the duration of depressive symptoms following widowhood vary between individuals (Hopf. et al. 2020). Despite these similar consequences for stress responses, and that individuals might reasonably be exposed to both stressors at the same time, very little is known about the interaction between the two.

This lack of analytical crossover between life course research on widowhood and epidemiological research on air pollution is in part due to these research streams being housed in separate disciplines. Existing research on widowhood and mental health typically studies the role of social variables, such as gender or contact with children, as relevant moderators (Schaan, 2013; Schmitz, 2021; Peña-Longobardo et al. 2021; Jadhav and Weir, 2018). Existing research on the association between air pollution and depressive symptoms typically makes use of hospital data (e.g. Newbury et al. 2021) or non-representative cohort studies (e.g. Altuğ et al. 2020). Nationally representative work is frequently confined to country specific analyses (e.g. Pun et al. 2016; Park et al. 2024; Petrowski et al. 2021). A notable exception is work by Zijlema et al. (2016), which considers a sample from four large European cohorts. Among these representative studies, results concerning an association between particulate matter and increased depressive symptoms are somewhat mixed.

This existing literature typically takes a cross-sectional, as opposed to a longitudinal approach. Scoping reviews in environmental demography have frequently pointed out how a lack of nationally representative, longitudinal data that is linked with meteorological variables has limited the study of how exposure to environmental hazards affects individuals over time (Grace, Merchant and Nagle, 2025; Tipaldo, Balk, and Hunter, 2024; Muttarak, 2021). These data limitations have meant that environmental demography and related disciplines have typically analyzed moderators of the relationship between air pollution and health that are visible at a cross-sectional level, such as education level or income. The role of life events, due to their temporal specificity, has been underresearched in comparison. Therefore, I consider **to what extent air pollution acts as a moderator of depressive symptoms associated with widowhood in the European context.**

To address this question, I employ a newly available dataset, SHARE-ENV (Midões et al. 2024), which is a version of the Survey of Health Aging and Retirement in Europe (SHARE) linked with environmental data. To my knowledge, this is the first analysis using this dataset to discuss the role of widowhood and air pollution upon depressive symptoms. With this longitudinal approach, I am able to observe the introduction of a common yet critical life stressor (widowhood) in tandem with population-weighted particulate matter exposure. I consider a nationally representative sample of eleven European countries with a similar level of data quality. Upon this data, I apply mixed effects regressions to consider the relationship between widowhood and depressive symptoms, and air pollution and depressive symptoms separately. I observe that widowhood is a sudden onset stressor which leads to a sharp increase in symptoms in its own right, with a return to baseline symptoms at three or more years following widowhood. On the contrary, significant levels of particulate matter exposure are relatively stable over time and are accompanied by less direct consequences on depressive symptoms. Next, I consider an interaction term of widowhood and air pollution. A key finding of this work is that I find that the presence of particulate matter is associated with increased levels of depressive symptoms three or more years following widowhood.

I make a theoretical and empirical contribution with this analysis. The theoretical contribution is the consideration of air pollution as a relevant moderator of depressive symptoms following widowhood, alongside typically considered variables such as social contact and gender. The empirical contribution is that these findings suggest that air pollution may not be a sufficient factor in producing depressive symptoms among older adults. Instead, it may instead act in tandem with existing life stressors by aggravating responses to these more sudden shocks. I hypothesize that this is one possible explanation for the current state of mixed results in the association of particulate matter exposure and depressive symptoms in nationally representative cross-sectional literature. This work has some policy ramifications, specifically regarding who is considered most vulnerable to the adverse mental health effects of air pollutants. I posit that vulnerability to the mental health effects of air pollution may vary over the life course in conjunction with the timing of critical yet common life events such as widowhood, instead of vulnerability being a uniquely static function of fixed sociodemographic traits.

2. Previous Research on Depression, Air Pollution, and Widowhood

2.1 Depression, Stress, and Widowhood

There are several models through which to understand the bereavement process both at a psychological and a neurobiological level, specifically regarding the role of the stress hormone cortisol. Beginning at the psychological level, Stroebe and Schut (1999) propose a dual process model of bereavement. In contrast to more static models, such as the five stages of grief, Stroebe and Schut (1999) propose a conception of grief wherein individuals oscillate between loss oriented and restoration grief, or at times pausing from grief entirely. Loss oriented grief is most closely associated with the acute stages of bereavement. Such reactions are painful, but a psychologically normal reaction to personal loss, and typically improve in the span of one to two years. In some cases, profound loss oriented grief may be experienced in the medium term following bereavement. This is also referred to as complicated or prolonged grief, wherein individuals struggle to ever return to their daily activities, remaining in a prolonged depressive state (Mason, Tofthagen and Buck, 2020).

This conception of grief has important overlaps with the "healthy aging" framework common in gerontological literature. Within the healthy aging framework, adverse circumstances in older age are expected, and to a certain extent, unavoidable. Healthy aging entails harboring resilience in the face of these challenges, eventually returning to a baseline quality of life for the remaining years of one's life. Consequently, understanding factors of how normal grief may transition into prolonged grief holds an importance within the context of population aging. Individuals with prolonged grief may struggle to maintain current social relationships or form new social connections, which is linked to various adverse mental or physical health outcomes. Therefore, prolonged grief contains both direct and indirect risks to the healthy aging of a bereaved older adult.

Bereavement is associated not just with grief and sadness but also stress. A stress response is typically defined as the activation of the hypothalamic-pituitary-adrenal (HPA) axis, a neuroendocrine system responsible for regulating stress. The release of cortisol from the adrenal gland is a key marker of such a response. Stress responses may be intertwined in psychological reactions to loss, particularly in relation to the circumstances of death of the deceased. For example, Richardson et al. (2015) find that widowhood is associated with increased levels of the stress hormone cortisol up to 18 months following spousal loss, which is longer than had been reported in previous analyses. A systematic review by Hopf. et al. (2020) confirms a persistent finding of changes in cortisol levels among individuals experiencing bereavement, though they note this body of research is still in its early stages, and could benefit from more precise measures of grief, and more longitudinal analysis. Regarding prolonged grief more specifically, a literature review by Mason and Duffy (2018) finds that dysregulation in cortisol levels was consistently observed among individuals experiencing complicated grief. This suggests that neuroendocrine mechanisms of grief are important in understanding medium term mental health outcomes following bereavement.

Another key element associated with the activation of the HPA-axis is inflammation. In the short term, the activation of the HPA-axis has anti-inflammatory properties, but where it is in a state of chronic activation, such as in prolonged grief, it may become dysregulated and increase inflammation. For example, a study by Cohen et al. (2015) finds an association between bereavement and the presence of biomarkers suggesting inflammation. This raises new questions on potential feedback loops, as inflammation is increasingly seen as a key factor of many adverse physical and mental health outcomes, including depression (Yin et al. 2024) and frailty (Soysal et al. 2016). Taken together, these findings suggest the relevance of stress responses when considering the mental health effects of bereavement in both the short and medium term. Given the extensive psychological and neuroscientific literature detailing the temporality and mechanisms of bereavement, I consider the following hypothesis: *widowhood is associated with depressive symptoms in the short term (H1).* I define the short term as the year of widowhood to two years following widowhood, in line with the most common durations of bereavement (Stroebe and Schut, 1999) However, I note the interest the possibility that depressive symptoms may be observed beyond the short term windows, and therefore allow for the possibility to observe depressive symptoms up to three or more years following widowhood.

2.2 Depression and Air Pollution

Recent years have seen an increased interest in understanding the health risks of air pollution, especially among vulnerable groups such as older adults. Fundamentally, exposure to air pollution acts as a catalyst for inflammatory response. This means that it is associated with a variety of adverse health outcomes, including epigenetic aging (Van Dang et al. 2025). Advances in neuroscience have also shown that air pollution is associated with adverse mental health outcomes, such as Alzheimer's and related dementia diagnoses (Livingston et al. 2024), and importantly for this analysis, depression (Cativiela-Campos et al. 2025). This research has emphasized similarities in how biological responses to air pollution are similar to those in response to chronic stress. Specifically, the presence of particulate matter in the bloodstream by way of inhalation and lung absorption may trigger inflammation and thereby a response from the HPA-axis (Snow et al. 2018). Similar findings have also been reported in exposure to NO2 (Yao et al. 2022; Wing et al. 2018) though the body of research on particulate matter is further developed.

Many studies on particulate matter exposure and depressive symptoms are based on smaller cohorts recruited through specific clinics or randomized control trials (e.g. Gatto et al. 2025). Comparatively fewer studies rely on nationally representative samples of older adults, and among these studies findings are mixed. Pun et al. (2016) find that in the American context, exposure to particulate matter smaller than 2.5 micrometers in diameter (PM 2.5) is associated with increased anxiety and depressive symptoms, and that this relationship is stronger among individuals of lower socioeconomic status. Zare Sakvhidi et al. (2022) find in the French context PM 2.5, Black Carbon and NO2 are positively associated with depressive symptoms, and this relationship was larger among respondents with lower income and education levels. In contrast, a study of four European large cohort samples by Zijlema et al. (2016) finds no consistent link between air pollution exposure and depressive symptoms. Though nationally representative studies have not reached identical conclusions, I consider that the substantial body of evidence from neuroscience regarding the mechanisms of air pollution and depressive symptoms means that I may hypothesize that *particulate matter is associated with depressive symptoms (H2).*

2.3 Considering the Role Multiple Stressors on Mental Health Outcomes

While previous research suggests that air pollution and bereavement are separately associated with negative health outcomes, these stressors may plausibly affect individuals at the same time. In Figure 1, I modify the theoretical framework of Thomson (2019) in order to elaborate on the overlapping stress responses considered in this analysis and consequent hypotheses of this work.

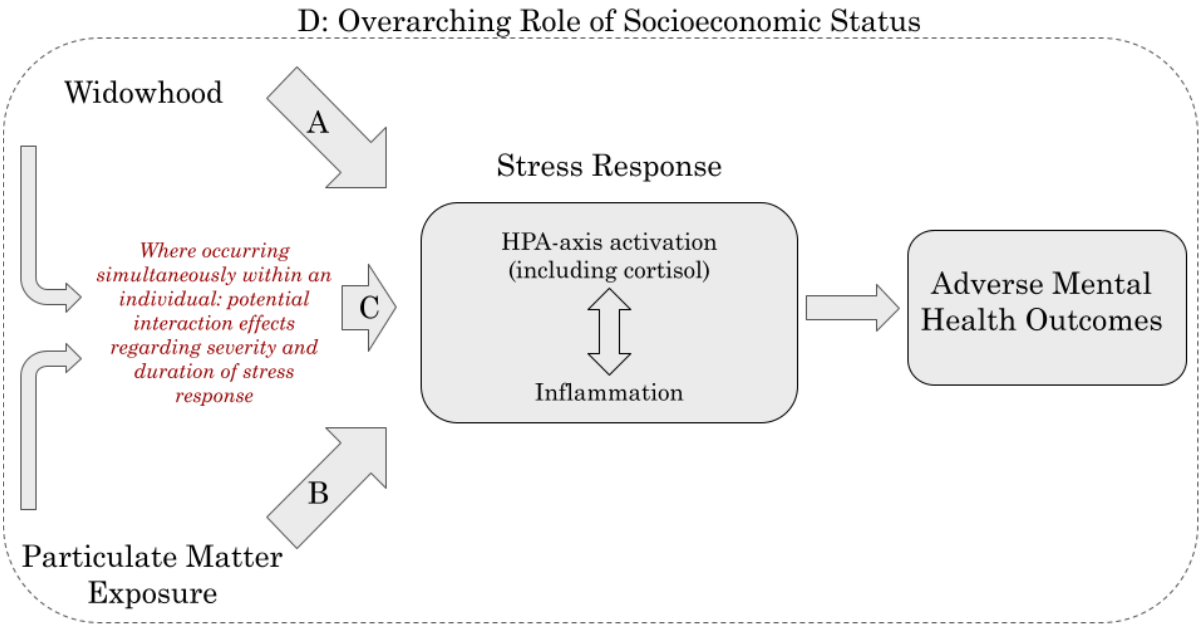

Figure 1. Theoretical Framework: Interaction of Widowhood and Air Pollution Stress Response

Arrows A and B correspond to H1 and H2, respectively, concerning the direct role of widowhood and particulate matter exposure as stressors in their own right as discussed in the above sections.

Next, I move to consider possible interaction effects between these two stressors. Existing studies on limited samples have suggested that individuals with existing adverse mental health conditions, and related HPA-axis activation, are indeed more susceptible to adverse mental health outcomes associated with air pollution related HPA-axis activation than individuals who do not harbor these same underlying mental health conditions. A study by Miller et al. (2015) on 130 adolescent girls finds that PM 2.5 exposure was associated with an HPA-axis responsivity among individuals who reported more serious levels of anxiety only: they did not find a main effect of PM 2.5 on HPA-axis responsivity among those who did not report anxiety. Work by Ailshire et al. (2017) in the United States finds that neighborhood social stressors worsened susceptibility to particulate matter related cognitive decline. A recent study by Zou et al. (2025) using a nationally representative sample in Chinese context and a cross-sectional analytical approach, finds heterogeneity in the relationship between air pollution and depression scores according to marital status, with widowed individuals being more susceptible than married adults (though time since widowhood is not considered). While these studies may explore heterogeneous vulnerabilities in individuals, these are typically cross-sectional, and less is known about the temporal dynamics behind these associations, or the role of time variant moderators, such as widowhood. Nevertheless, the existing evidence discussed suggests that experiencing life stress and air pollution exposure simultaneously may increase susceptibility to adverse mental health outcomes associated with each stressor. I therefore consider the following hypothesis: *affective suffering associated with widowhood is modified by exposure to particulate matter (H3)* seen in Figure 1 as arrow B.

2.4 The Role of Socioeconomic Status in Exposure and Susceptibility to Multiple Stressors

Another relevant dynamic in addition to air pollution exposure and individual sensitivity is the role of contextual stressors, such as socioeconomic status, which reflects both acute and lifetime differences in stress and exposure to other health risks (Thomson, 2019). Epidemiological literature, especially in the US context, has noted that socioeconomic status may be an important confounding factor on the effects of air pollution on health outcomes. This is because exposure to air pollution may be spatially heterogeneous according to socioeconomic status. Socioeconomic status may be correlated with other factors such as smoking, diet, healthcare access and so on may also affect one's susceptibility to air pollution. In other words, individuals of lower socioeconomic status may at once be more exposed to air pollution and more susceptible to adverse health effects from it. For instance, a study by Clougherty (2022) finds that in the case of US cities it is difficult to disenagle the relationship between race, socioeconomic status, and exposure and susceptibility to air pollution related health effects because of race-based redlining and long- term discriminatory practices. However, environmental inequality frameworks developed from the US historical context may not be perfectly transferrable to Europe. Research has generally found a strong socioeconomic gradient in exposure in the US, while in Europe these results are more mixed (Hajat et al. 2015). For instance, some research has found that ethnic background is a stronger determinant of air pollution exposure than socioeconomic status in some European contexts (Van Den Brekel, 2024).

The longitudinal design of this analysis, and the ubiquity of widowhood as a stressor, may act as a useful case for this literature. While widows in this sample have less years of education on average compared to continuously married individuals, widowhood is not a life event that individuals of higher education/socioeconomic status are completely isolated from. I therefore consider two subsamples of the overall sample: one with above median years of education and one with below median years of education. If the interaction effect between air pollution and affective suffering is different between these two groups, that would suggest that individuals of lower education/socioeconomic status are more susceptible to this dynamic due to exposure to stress over the life course, and other health morbidities associated with socioeconomic inequalities. Given the potential relevance of contextual stressors alongside acute stressors such as widowhood, and environmental stressors such as air pollution, I consider the following hypothesis: *the role of air pollution on widowhood related affective suffering is larger among individuals of lower socioeconomic status (H4).* The relevance of socioeconomic status as an overarching determinant of both exposure to risk and vulnerability to adverse outcomes due to those risks is illustrated in Figure 1 by box D.

3. Data

I employ the Survey of Health, Aging and Retirement in Europe (SHARE). SHARE is a cross-national household panel survey that contains information on physical and mental health, socioeconomic status, and social networks of the respondents. This survey includes individuals who are 50 years old or more, with information collected on a biennial basis since 2004. We exclude the third wave of SHARE, also referred to as SHARELIFE, which contained a retrospective life history module as opposed to the variables collected in other waves. Consequently, I collect observations from the first, second, fourth, fifth, sixth, and seventh waves of SHARE (2004-2019). I also consider SHARE-ENV, an extension of the Survey of Health Aging and Retirement in Europe (SHARE) with a variety of population-weighted and georeferenced environmental variables. Environmental data is linked with SHARE respondents via the respondent location as provided in the housing module in regular waves of SHARE. Within SHARE, respondent location is typically reported at the regional (NUTS-2) level. This is the case in the following countries: Austria, Bulgaria, Croatia, Czechia, Denmark, Finland, Greece, Italy, Latvia, Lithuania, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden. A few countries do not report regional respondent location, only national information is available (NUTS-1). These countries are Belgium, France, and Germany, which are nevertheless included in SHARE-ENV (Midões et al. 2024: Supplementary Information, S4).

4. Methods

4.1 Sample

We consider European countries that have been included in the survey for five or more waves which permits us to observe both the transition to widowhood and medium-term recovery, and countries that SHARE-ENV provides population-weighted particulate matter data for. These conditions yield the eleven following countries: Austria, Belgium, Switzerland, Czechia, Germany, Denmark, Spain, France, Greece, Italy, Poland, Sweden and Slovenia. From this set of countries, I then consider only individuals who remain married continuously throughout all observations, and individuals who experience a transition to widowhood. I include widowed individuals even in the case of re-partnering during the window of observation, as this contributes to post-bereavement recovery.

4.2 Focus Variables

4.2.1 Affective Suffering

SHARE includes a battery of 12 depressive symptoms, the EURO-D metric, in each of its waves. These questions include if a respondent has a depressed mood, pessimistic, is suicidal, guilty, has trouble sleeping, changes in general interest, more irritability, changes in appetite, fatigue, concentration, enjoyment and tearfulness. Typically, researchers opt to take a sum score of these symptoms, or collapse the metric into a binary variable, taking either the first question as self reported depression, or considering a benchmark of 3 or 4 symptoms as depressed as proposed by the creators of the metric: Prince et al. (1999). However, some recent research has suggested that considering clusters of symptoms within the metric may improve the cross-national measurement validity of the metric, and yield substantively different findings where researchers may previously treat all depressive symptoms as identical (Castro-Costa et al. 2008: Maskileyson et al. 2021).

I consider a factor score of affective suffering, the first factor in the EURO-D metric, as my outcome variable of interest. After testing the metric in 14 European centers, Prince et al. (1999) noted in their initial establishment of the metric that the EURO-D score may be decomposed into two factors. The first factor is affective suffering: self-reported feelings of sadness or tearfulness load heavily onto this factor. This factor is more closely related to typical experiences of bereavement seen in the short term following loss (Stroebe and Schut, 1999). An extension of these symptoms to the medium term may signify the presence of complicated grief. (Szuhany et al. 2021). Several studies have affirmed the cross-national validity of the affective suffering factor, in contrast to the EURO-D sum score, which is suitable for within-country studies but unstable in comparative work (Castro-Costa et al. 2008: Maskileyson et al. 2021). The second factor is associated with changes in motivation: feelings of pessimism and lack of interest (a subset of depressive symptoms also referred to as anhedonia) load most heavily onto this factor. While both of these clusters of symptoms carry negative consequences for quality of life, they both have distinct patterns within dynamics of bereavement, therefore necessitating a focus on a given factor in isolation.

4.2.2 Particulate Matter

I consider the concentration of particulate matter smaller than 2.5 microns in diameter (PM 2.5) and the concentration of particulate matter smaller than 10 microns in diameter (PM 10). I consider particulate matter due to the more advanced state of epidemiological and neuroscientific literature on the adverse consequences and specific mechanisms of particulate matter exposure compared to other pollutants. From SHARE-ENV, I use the population-weighted yearly average of the monthly mean concentration of PM 2.5 and PM 10 at the NUTS-2 (regional) level at the year of the survey wave across responses. These values are expressed in terms of micrograms per meter cubed ($\mu g/m^3$). This data is derived from CAMS, the section of the EU Copernicus data center focused on air pollution, and then bilinearly interpolated to match SHARE regions.

Air pollution data collected from the late 1990s onwards in Europe generally relies on an improving network of in-situ measurement sites across continents. In contrast, exposures suffered earlier in the life course of SHARE respondents (1950s onwards) are usually based on historical emissions data, not direct measurements, which increases the degree of uncertainty in such measures. In this analysis, I consider short/medium term exposure due to the lower level of uncertainty associated with air pollution data collected during the window of the SHARE survey. While future research may seek to expand the analysis at hand to encompass earlier life exposures, I consider that the differences between these two data sources are significant enough to be considered as discrete research endeavours.

4.3 Estimation Technique

I employ a between-within random effects linear regression model (Allison, 2009; Bell and Jones, 2015), though the findings presented here are consistent when employing a similar within-transformation fixed effects estimator. The main explanatory variable, duration of widowhood, is expressed both as a categorical variable, and individual level averages of binary indicators for each level of the categorical variable. Here, I consider within individual change relative to a reference group, not within individual means. Computationally, this is very similar to the generic approach outlined by Allison (2009) since the factor variable is treated as a series of dummy variables but I achieve the following benefits: I permit a nonlinear effect shape while maintaining easily interpretable coefficients. This may be specified as follows:

$$y_{itc} = \beta_0 + \overline{D}_i\beta_1^{BE} + \left(D_{it} - \overline{D}_i\right)\beta_1^{FE} + X\beta + u_i + u_c + e_{itc}$$

The main explanatory variable, duration of widowhood, is expressed both as a time constant variable ($\overline{D}_i\beta_1^{BE}$) and time-varying ($\left(D_{it} - \overline{D}_i\right)\beta_1^{FE}$) variable. The focus lies on the latter, which delivers an estimate of average within-individual change in affective suffering two years before spousal death, one year before spousal death, the year of spousal death, one or two years afterwards, and three or more years afterwards, compared to continuously married individuals or widowed individuals three or more years ahead of spousal loss. I include random intercepts at the individual (u_i) and country level (u_c). I also include controls for which portion of the sample an individual belongs to (continuously married or widowed), gender, age, years of education, income (z-scored) and survey wave ($X\beta$), and an idiosyncratic error term.

Crucially, this analysis only includes individuals where I am able to observe a transition into widowhood within the context of the SHARE survey. This is in contrast to existing cross-sectional approaches, where the timing effects between life stressors and air pollution exposure and consequent mental health outcomes is under explored. I then interact time varying, time to or since widowhood variable with each air pollution variable in turn.

5. Results

5.1 Descriptive Statistics

Table 1. Sample Descriptive Statistics by Country and Overall: Means and Percentages, with Standard Deviations in Parentheses.

Country	Sample	N	Age	Education	Male	Female	Factor Score	PM 2.5	PM 10
AT	Continuously Married	3281	65 (8.9)	9.2 (4.7)	49.3% (1618)	50.7% (1663)	-0.13 (0.9)	15.01 (2)	21.11 (2.81)
AT	Widowed	263	72.3 (9.1)	8.1 (3.8)	30.4% (80)	69.6% (183)	0.15 (0.99)	15.16 (2.09)	21.31 (2.92)
BE	Continuously Married	5837	63 (9.3)	12.6 (3.7)	48.2% (2814)	51.8% (3023)	0.08 (0.97)	19.22 (3.68)	27.68 (5.11)
BE	Widowed	381	73.3 (9.9)	11.3 (3.4)	33.6% (128)	66.4% (253)	0.2 (0.99)	20.09 (3.64)	28.88 (5.06)
CH	Continuously Married	2828	64.6 (9.2)	9.1 (5.4)	48.4% (1368)	51.6% (1460)	0.09 (0.94)	11.73 (1.45)	16.62 (2.01)
CH	Widowed	209	74.4 (8.9)	8.5 (4.6)	32.5% (68)	67.5% (141)	0.25 (0.99)	11.93 (1.36)	16.88 (1.88)
CZ	Continuously Married	4642	64.5 (8.5)	12.5 (3)	48.6% (2258)	51.4% (2384)	-0.02 (0.91)	17.85 (3.02)	25.32 (4.21)
CZ	Widowed	414	71.3	11.8	24.4%	75.6%	0.27	17.78	25.22

			(8.2)	(3.1)	(101)	(313)	(0.98)	(2.85)	(3.97)
DE	Continuously Married	5785	64.2 (9)	12.9 (3.5)	48.9% (2830)	51.1% (2955)	0.11 (0.95)	14.92 (3.23)	21.41 (4.5)
DE	Widowed	342	70.4 (9.3)	12.2 (3.3)	33% (113)	67% (229)	0.37 (0.98)	14.89 (3.37)	21.41 (4.67)
DK	Continuously Married	3268	62.3 (8.6)	13.9 (3.3)	47.8% (1562)	52.2% (1706)	-0.05 (0.88)	9.17 (1.05)	13.97 (1.52)
DK	Widowed	310	72.2 (9.7)	12.7 (3.5)	34.5% (107)	65.5% (203)	0.14 (0.96)	9.55 (1.15)	14.54 (1.62)
ES	Continuously Married	5320	65.5 (9.6)	9.2 (5.1)	48.6% (2584)	51.4% (2736)	-0.15 (0.9)	11.77 (2.06)	16.79 (2.82)
ES	Widowed	572	75.9 (9.2)	5.8 (4.3)	22.9% (131)	77.1% (441)	0.08 (0.98)	12.27 (2.31)	17.49 (3.17)
FR	Continuously Married	2710	63.3 (9.7)	12.1 (4.1)	49.2% (1333)	50.8% (1377)	0.17 (1)	18.67 (6.63)	26.76 (9.24)
FR	Widowed	229	73 (10.2)	10.6 (3.6)	27.5% (63)	72.5% (166)	0.31 (0.98)	17.67 (5.71)	25.33 (7.97)
GR	Continuously Married	4044	62.7 (9.4)	9.9 (4.2)	48.8% (1975)	51.2% (2069)	-0.29 (0.84)	14.86 (2.93)	20.81 (4.09)
GR	Widowed	305	72.4 (9.2)	7.1 (3.8)	17.7% (54)	82.3% (251)	-0.09 (0.94)	15.37 (2.91)	21.52 (4.07)
IT	Continuously Married	5565	64.4 (9)	9.2 (4.4)	48.4% (2696)	51.6% (2869)	-0.1 (0.93)	18.84 (5.89)	26.61 (8.17)
IT	Widowed	414	72.7 (8.8)	6.3 (3.5)	25.8% (107)	74.2% (307)	0.08 (1.01)	19.56 (6.08)	27.62 (8.44)
PL	Continuously Married	3911	63.1 (8.4)	10.7 (3.1)	47.9% (1872)	52.1% (2039)	0.06 (1.06)	14.63 (4.26)	20.9 (5.91)
PL	Widowed	318	70.5 (9.3)	8.8 (3.2)	29.9% (95)	70.1% (223)	0.17 (1.07)	15.49 (4.55)	22.06 (6.33)
SE	Continuously Married	3907	66.5 (8.8)	12 (3.9)	48.6% (1899)	51.4% (2008)	-0.08 (0.9)	6.84 (1.66)	10.17 (2.37)
SE	Widowed	371	74.8 (9.2)	10.3 (3.8)	32.9% (122)	67.1% (249)	0.13 (0.98)	6.84 (1.78)	10.16 (2.53)
SI	Continuously Married	3559	64.6 (8.6)	10.9 (3.3)	48.6% (1728)	51.4% (1831)	-0.07 (0.96)	16.6 (1.2)	23.42 (1.66)
SI	Widowed	264	72 (9.2)	9.9 (2.9)	26.9% (71)	73.1% (193)	0.05 (1.01)	16.52 (1.22)	23.31 (1.69)
Entire Sample	Continuously Married	54657	64.2 (9.1)	11.1 (4.4)	48.6% (26537)	51.4% (28120)	-0.03 (0.94)	15 (5.12)	21.43 (7.1)
Entire Sample	Widowed	4392	73 (9.4)	9.4 (4.4)	28.2% (1240)	71.8% (3152)	0.16 (0.99)	14.96 (5.23)	21.38 (7.25)

Table 1 describes the makeup of our selected sample, separated by continuously married individuals (featured in our reference group) and individuals where I may observe a transition into widowhood. Expectedly, widowed individuals in the sample tend to be older than continuously married individuals: the average age of widows in our sample is 73 years old, compared to 65 years old among continuously married individuals (a difference of 8 years). The average age of widows also varies by country, mirroring trends in regional life expectancy across Europe: Spain, Sweden, Switzerland, and Greece contain the oldest widowed population, with Eastern European countries such as Poland and the Czech Republic containing the youngest widowed population. Also expected is that women are featured prominently in the widowed sample, making up around two thirds of the widowed sample, whereas the continuously married sample features a more even gender split. I also observe that continuously married individuals on average have completed more years of education than those in the widowed sample.

I observe little difference in particulate matter exposure between widowed and continuously married individuals in the sample within countries, but a fair amount of between country heterogeneity. Across countries PM 2.5 and PM 10 exposure is typically higher than the most recent annual exposure WHO guidelines: 5 μg/m3 and 15 μg/m3 for PM 2.5 and PM 10, respectively (WHO, 2021). Belgium, the Czech Republic, and Italy contain some of the highest levels of PM 2.5 exposure. Due to increased policy attention in the past decades, PM exposure decreases through the window of analysis, but still remains above WHO recommendations in later waves in most countries (See appendix: Figure A1).

5.2 Widowhood, Air Pollution, and Affective Suffering

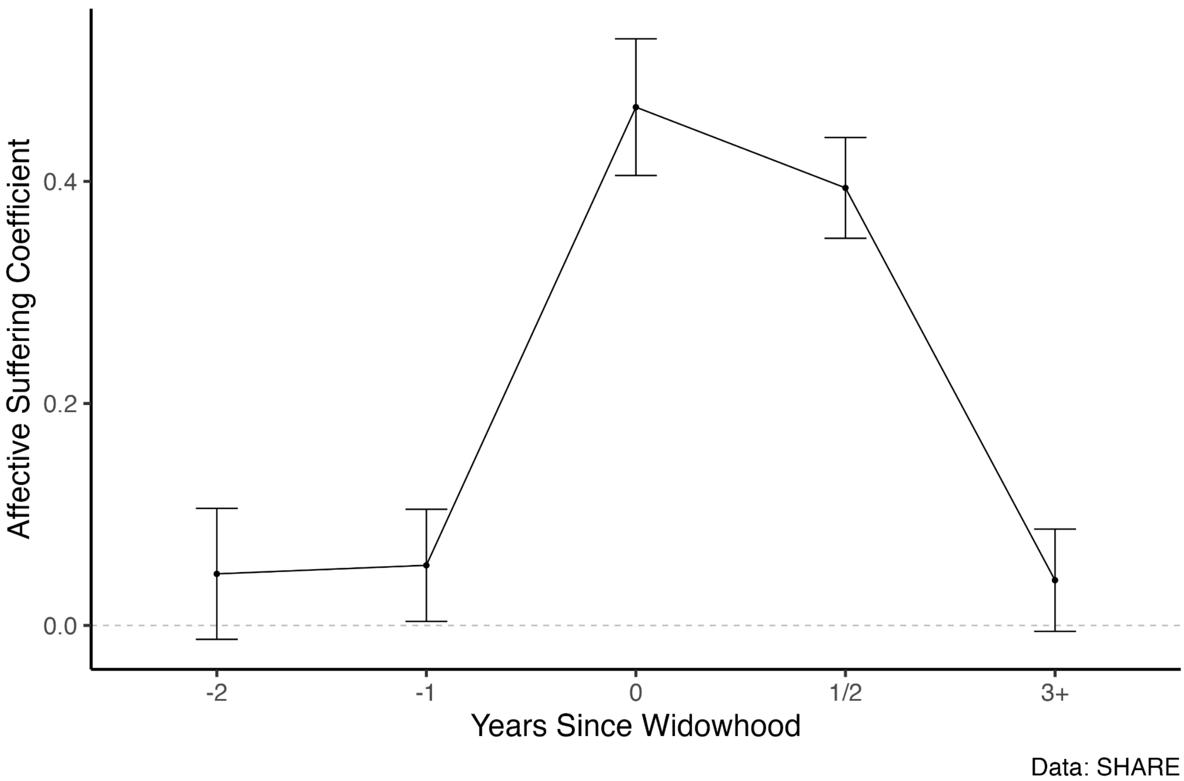

Figure 2. Change in Affective Suffering Associated with Widowhood Across Countries

Figure 2 displays the average within-individual change in affective suffering across the widowhood process relative to married individuals or those who are 3 or more years prior to widowhood. Change in affective suffering, displayed on the y-axis in Figure 2, is measured in standard deviations. Circles represent point estimates, and brackets represent 95 percent confidence intervals. The specification displayed here does not include any air pollution variables, either as controls or as interaction terms, in order to consider uniquely the role of widowhood on affective suffering.

In the two years prior to widowhood, I observe small, positive coefficients, with the estimate the year prior to widowhood being statistically significant at the 95 percent level. This is consistent with previous psychological and gerontological research on widowhood, which finds that widowhood especially among older adults may be preceded by several years of chronic illness on the part of the deceased spouse (see Kristiansen et al. 2019 for a systematic review of depression duration associated with widowhood). Again consistent with existing literature, the year of widowhood contains the highest point estimate of affective suffering across the window considered, with affective suffering scores being on average just under one half of a standard deviation above the reference group. Estimates decline slightly in the year or two following widowhood, before returning to levels similar to pre-widowhood levels in the medium term (3+ years after widowhood). Though the estimate here is insignificant, that the point estimate is positive suggests that some widowed individuals still report experiencing affective suffering at this stage. Taken together, these results confirm the first hypothesis of this work: *widowhood is associated with depressive symptoms in the short term (H1).*

Next, I consider whether air pollution is associated with increased affective suffering within the sample. In this specification, I remove time constant and time varying widowhood variables, but maintain all other controls.

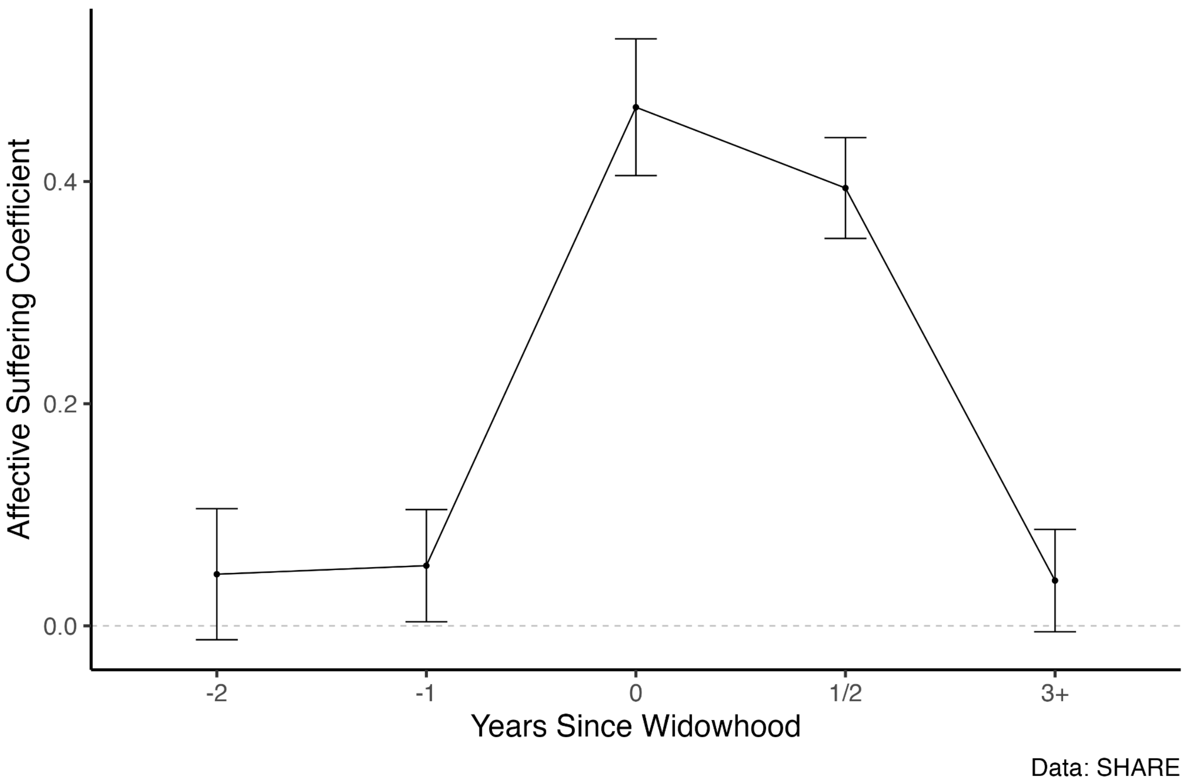

Figure 3. Change in Affective Suffering Coefficient Associated with Air Pollutants

Figure 3 displays model results from two successive models estimating the relationship between affective suffering and particulate matter. While these estimates are significant at the 95 percent confidence level, the estimated magnitude is much smaller and in the opposite direction (negative rather than positive) than that found in the interaction model displayed in Figure 4.

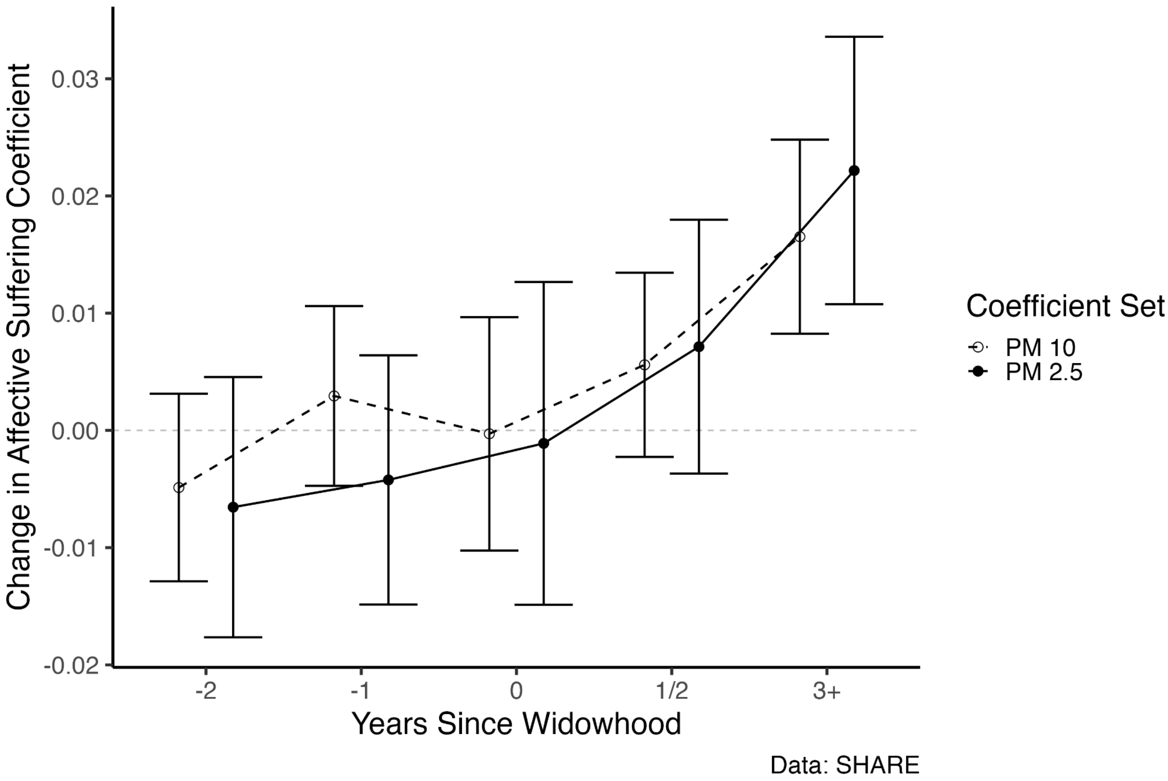

Figure 4. Change in Affective Suffering Coefficient Across Widowhood Associated with Air Pollutants

Figure 4 displays the estimated change in affective suffering throughout widowhood associated with a one unit increase in particulate concentration as measured in the yearly average of the given SHARE wave year. In this specification, the model is unchanged except for in three successive models, the addition of concentration of particulate matter to the within-individual time to/since widowhood measure. The results of only the interaction terms from each of the three models are presented here in the same plane to facilitate comparison. During the pre-widowhood period, there is no meaningful relationship. This is expected, since affective suffering under the core specification is also low at this point, and the baseline effect of particulate matter on affective suffering symptoms is relatively small. During the year of widowhood, there is likewise no strong interaction effect. Therefore, I cannot conclude that particulate matter attenuates affective suffering in the short term of bereavement.

In the short and medium term following spousal loss, the presence of both PM 2.5 and PM 10 are associated with an increase in affective suffering. This is especially noticeable at three or more years after widowhood. Here, a one unit increase in average PM 2.5 concentration is associated with around a 0.02 standard deviation increase in affective suffering. PM 2.5 values in the entire sample range from 3.57 to 39.57 (μg/m^3) meaning that one must keep in mind the interaction estimate is additive, not absolute. Similar results appear in both models, suggesting that this result is not confined to the particulate matter of smaller sizes.

Overall, I find that particulate matter does not modify the *severity* of affective suffering in the acute phase of widowhood. Instead, they modify the *duration* of symptoms, which raises concerns regarding the ability of affected individuals to return to their previous quality of life following bereavement. Together with the inconclusive interaction estimates at the pre-widowhood period, and the much smaller magnitude of the estimates reported in Figure 3, I conclude that the air pollutants included in this analysis may not be a convincing sufficient factor in triggering depressive symptoms. Therefore, I do not confirm hypothesis 2: *particulate matter is associated with depressive symptoms (H2).* Instead, these findings suggest that stress responses related to air pollution augment existing stressors, and disrupt returns to baseline levels of affective suffering. This confirms H3: *affective suffering associated with widowhood is modified by exposure to particulate matter.*

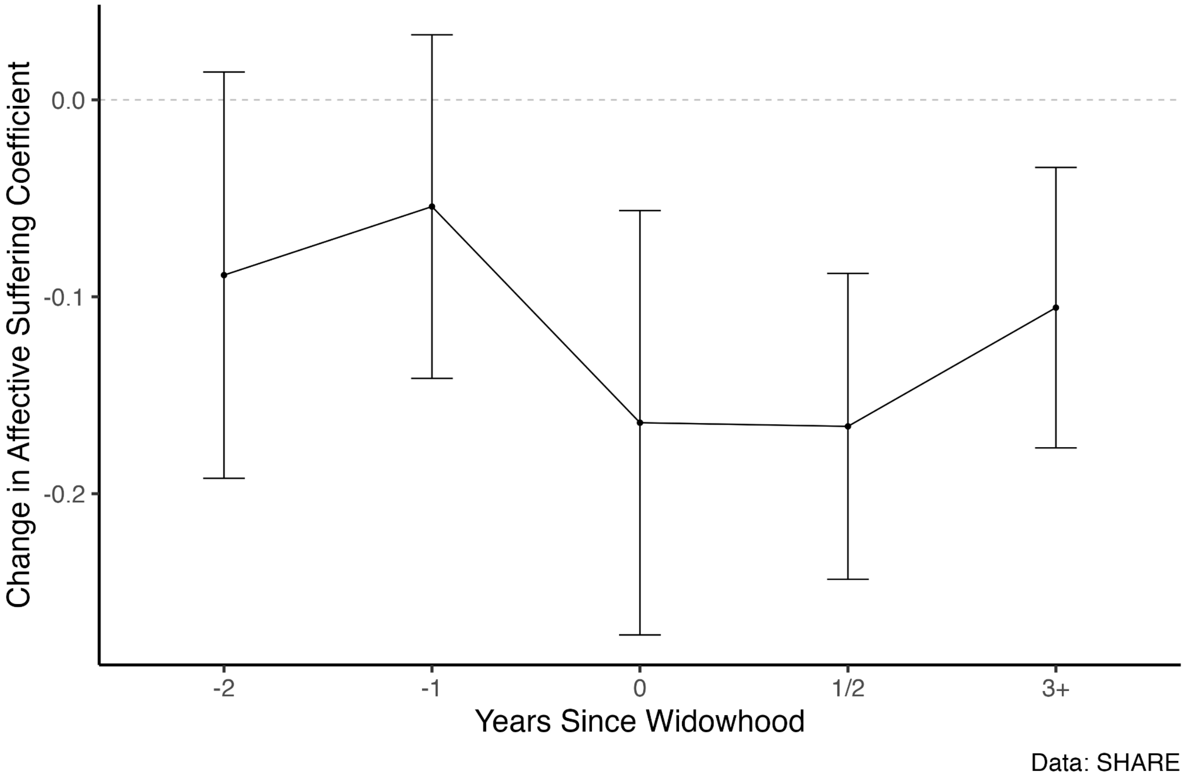

Figure 5. Change in Affective Suffering Coefficient Across Widowhood Associated with Median Education Binary

In this specification, I consider how the role of educational attainment may modify the relationship between widowhood and affective suffering, and the interaction effect between air pollution, widowhood, and affective suffering. Since the median number of years of education is 11 years in the sample overall, I first consider an interaction term in the core model with a binary term signifying where a respondent has less than 11 years of education. The results from this specification are displayed in Figure 5. The point estimates (circles) may be interpreted as the estimated change in affective suffering throughout the widowhood period associated with an individual having less than 11 years of education compared to individuals who have 11 or more years. I observe a decrease of one tenth of a standard deviation in affective suffering score associated with this distinction. This is somewhat in line with existing literature, which has not reached clear conclusions regarding the role of socioeconomic status in moderating depressive symptoms associated with widowhood (Kristiansen et al. 2019; Recksiedler et al. 2022).

Next, I create two subsamples by the same delineation of the binary term. Here, I do not include income as a control variable, but results are similar when it is included. For each subsample, I apply an interaction term to the time-varying widowhood term of PM 2.5 and PM 10 in turn, in order to compare the main interaction results shown in Figure 4 across educational subgroups. These results are displayed in Figure 6.

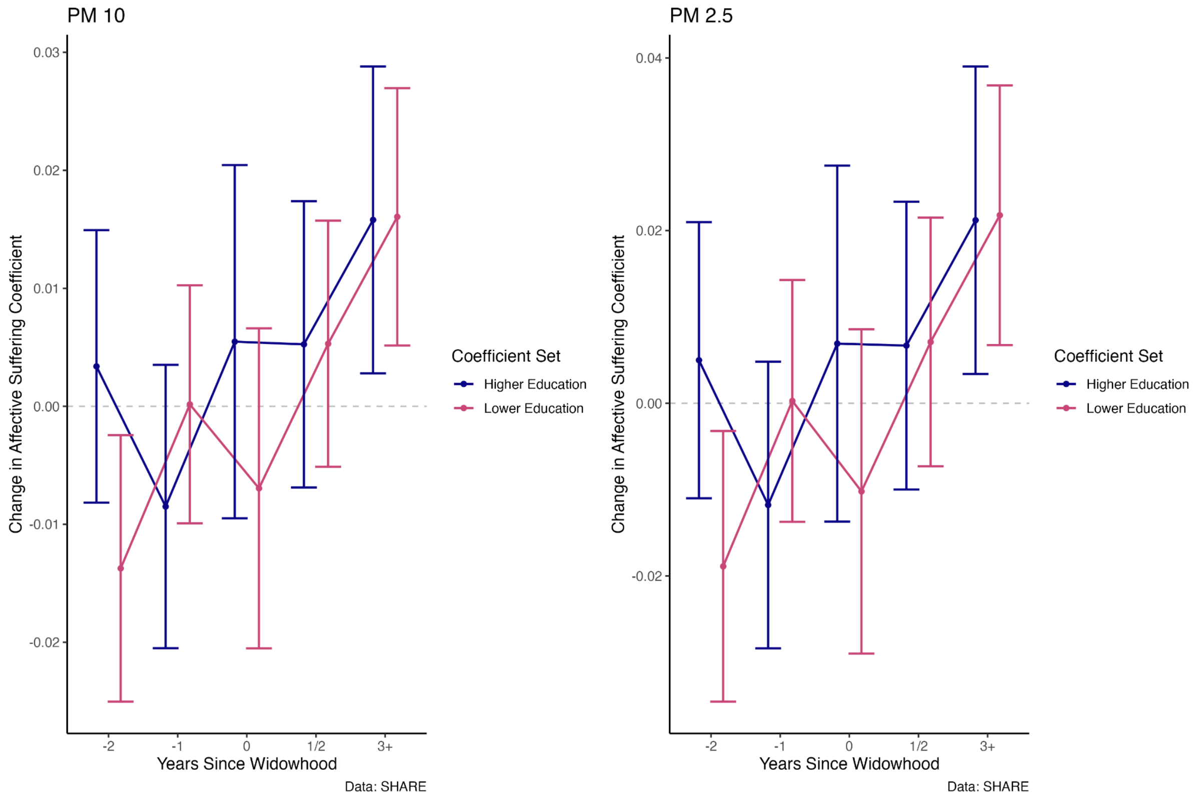

Figure 6. Change in Affective Suffering Coefficient Across Widowhood Associated with Air Pollutants Across Education Subsamples

Overall, the point estimates and confidence intervals of these interaction terms across the educational subsamples are nearly identical. At this juncture, I do not find evidence for hypothesis four: *the role of air pollution on widowhood related affective suffering is larger among individuals of lower socioeconomic status (H4).* This may, however, be the result of technical limitations, such as years of education serving as a coarse estimate of lifetime stress, or that exposure to air pollution is not spatially granular enough under SHARE to track differential levels of exposure at a local level.

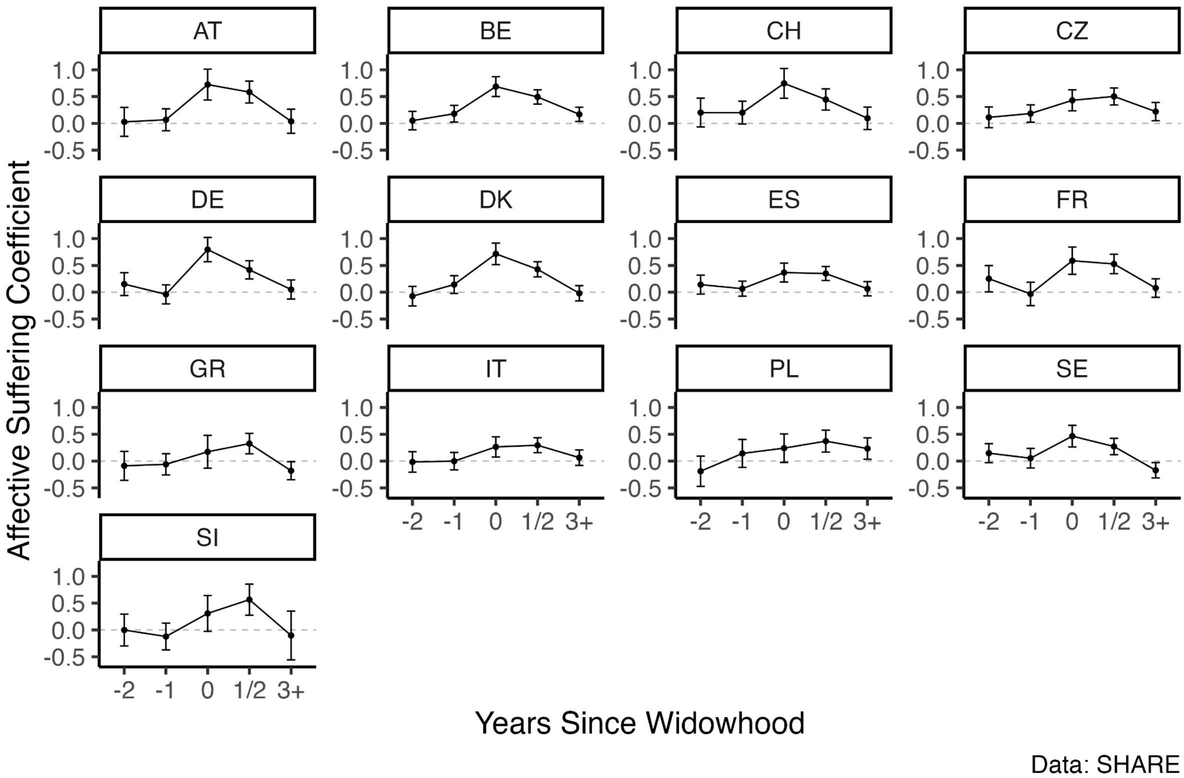

Figure 7. Widowhood and Affective Suffering Across Countries

Due to a limited country-specific sample size, I cannot test the interaction between air pollutants and affective suffering in each country separately. However, I am able to consider a by country analysis of the core model considering only widowhood and affective suffering. Focusing on the estimates at three or more years after widowhood, only three countries register estimates significant at the 95 percent confidence interval at this point: Belgium, Poland and the Czech Republic. Descriptively, in Table 1, I observe that two out of these countries, Belgium and the Czech Republic, saw higher levels of particulate matter compared to the rest of the sample. This especially true when focusing among later waves, which is when most of the widows in this sample would be three or more years post-widowhood (Figure 1A). Given the interaction effect found in the pooled analysis in Figure 4, elevated levels of particulate matter may be one factor driving these differences in the medium term seen in the Belgian and Czech sample. However, I cannot conclude that air pollution is the only possible explanation for higher affective suffering estimates in the medium term, since the third country in this group, Poland, contains relatively average levels of pollution.

6. Additional Analyses

I have also considered the core components of this analysis using a fixed effects estimator, with results under this specification included in the appendix (Figures 3A, 4A and 5A).

7. Conclusion and Next Steps

This analysis considered the role of air pollution as a moderator for depressive symptoms associated with widowhood across eleven European countries. This work seeks to fill a theoretical and empirical gap in the existing literature by exploring the role of time variant rather than time invariant moderators in the relationship between air pollution and mental health outcomes. I find that widowhood is associated with increased affective suffering in the short term, with no commensurate association observed for air pollution on its own. Instead, I observe that air pollution is associated with increased affective suffering observed in the medium term following spousal loss. This finding suggests that individuals experiencing a stressful life event, such as widowhood, are particularly vulnerable to the mental health risks of air pollution exposure. I do not find that this dynamic differs by educational level.

This study must be viewed in light of its limitations. First of all, while SHARE carries the advantage of a comparative scope, this means that air pollution exposure is measured at a much coarser level than commonly carried out in epidemiological literature. Another limitation is that socioeconomic status and related lifetime stress may be defined in many ways besides a binary measure of educational attainment. Therefore, some next steps for this work are to consider alternative measures of socioeconomic status or stress experienced over the life course. One possibility is through the consideration of early childhood circumstances in retrospective waves of SHARE (wave 3).

Another way to improve this analysis is to consider the differential effects of particulate matter from different sources, such as wildfire-specific particulate matter, given that wildfire specific particulate matter has been found to carry greater mental health risks compared to particulate matter from other sources (Zhang et al. 2023). This variable is not currently available through SHARE-ENV, but may be derived from data produced by Hanninen et al. (2022) to be congruent to SHARE regions. In this case, this data would be made open to other researchers seeking to link SHARE with air pollution exposures. Another variable that merits consideration is the role of temperature, given existing evidence on heat exposure exacerbating negative health effects associated with exposure to particulate matter (Chen et al. 2024). Furthermore, a future version of SHARE-ENV will consider weighing environmental variables by EU/OECD standard degree of urbanization (DEGURBA) of a given grid cell. It will then be possible to consider country or region specific weights of the degree of urbanity of a given spatial unit (Midões et al. 2024: Supplementary Information, S4). This would permit a reanalysis of the work presented here, but with more attention given to differential levels of particulate matter exposure experienced by urban and rural populations.

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9. Appendix

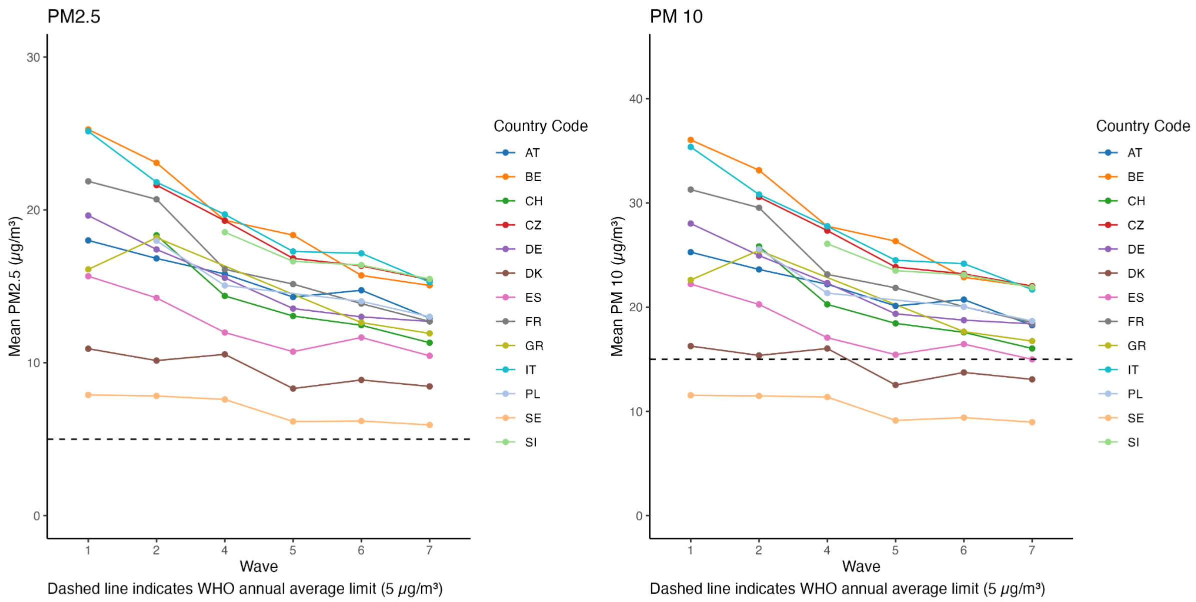

Figure 1A: Air Pollution By SHARE-ENV Survey Wave and Country

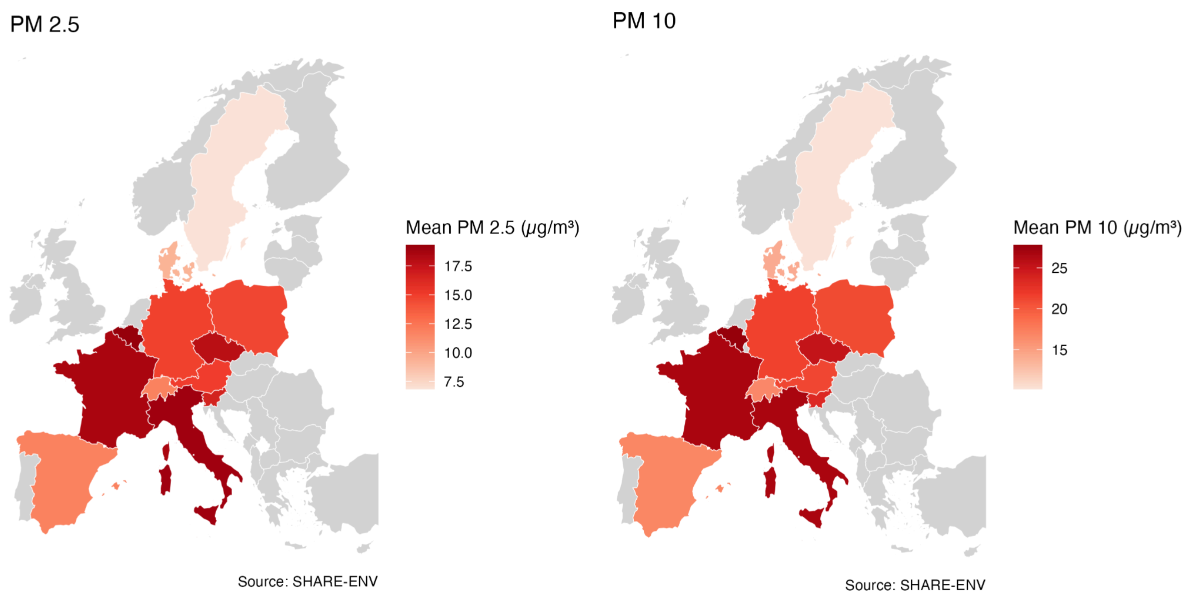

Figure 2A. Mean Air Pollutant Concentrations by Country Across All SHARE-ENV Waves

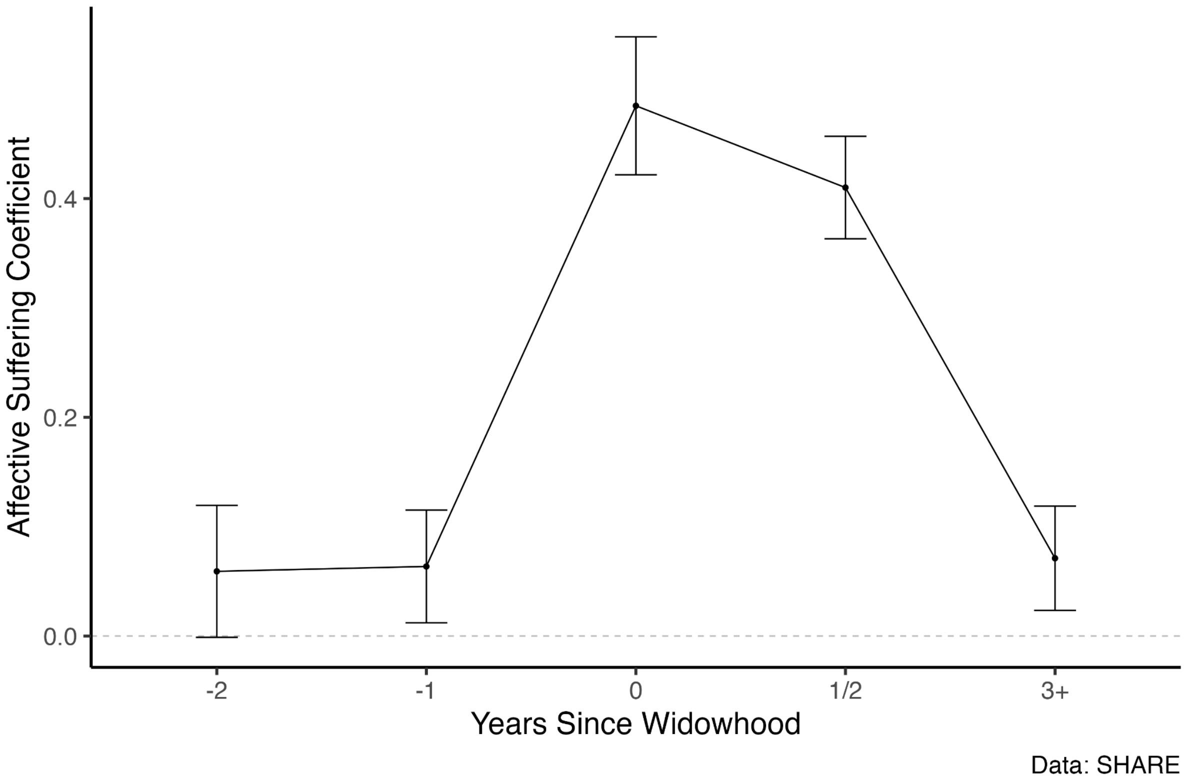

Figure 3A. Change in Affective Suffering Associated with Widowhood Across Countries: Fixed Effects

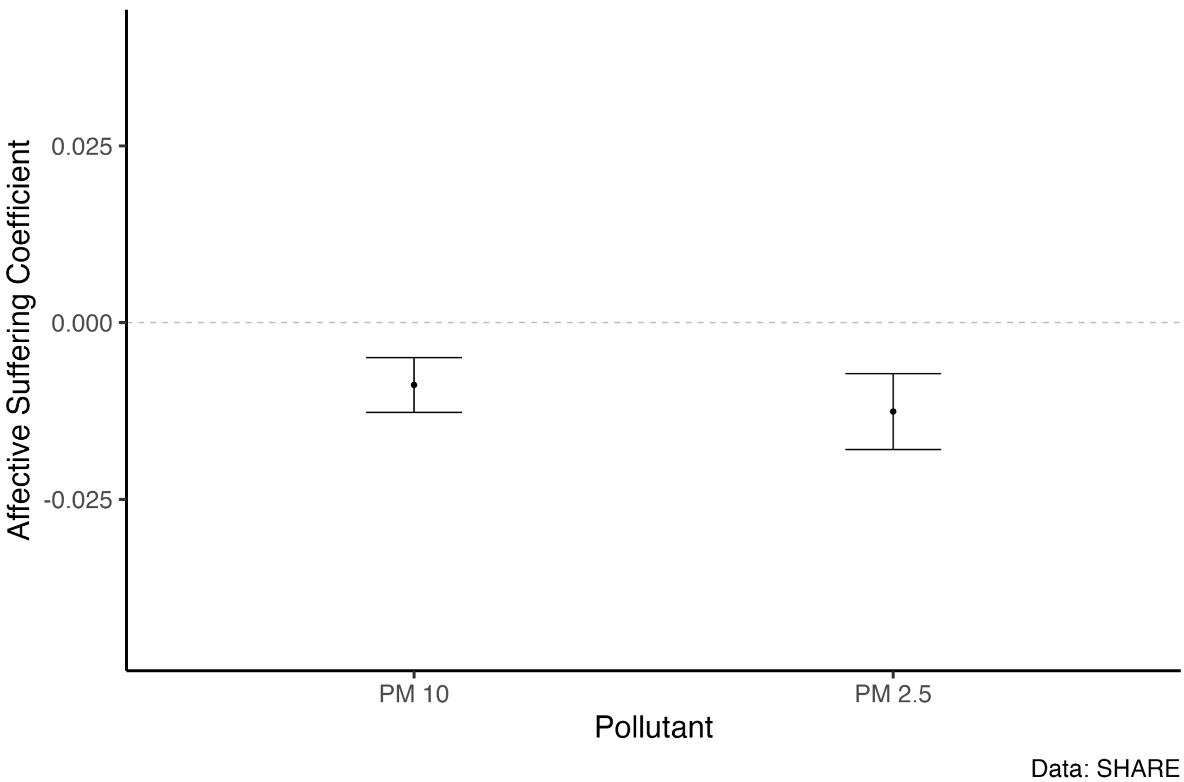

Figure 4A. Change in Affective Suffering Associated with Air Pollutants Across Countries: Fixed Effects

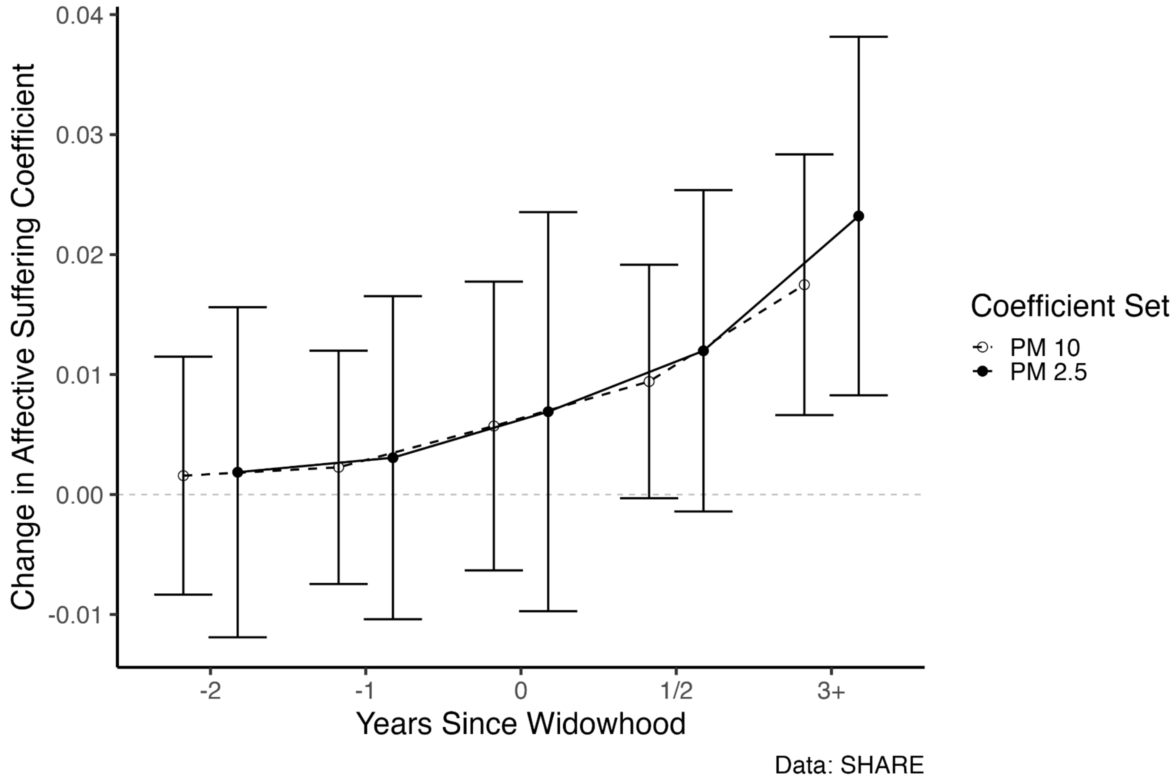

Figure 5A. Change in Affective Suffering Coefficient Across Widowhood Associated with Air Pollutants: Fixed Effects