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The long-run consequences of Chernobyl: Evidence on subjective well-being, mental health and welfare

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ABSTRACT

This paper assesses the long-run toll taken by a large-scale technological disaster on welfare, well-being and mental health. We estimate the causal effect of the 1986 Chernobyl catastrophe after 20 years by linking geographic variation in radioactive fallout to respondents of a nationally representative survey in Ukraine according to their place of residence in 1986. We exclude individuals who were exposed to high levels of radiation—about 4% of the population. Instead, we focus on the remaining majority of Ukrainians who received subclinical radiation doses; we find large and persistent psychological effects of this nuclear disaster. Affected individuals exhibit poorer subjective well-being, higher depression rates and lower subjective survival probabilities; they rely more on governmental transfers as source of subsistence. We estimate the aggregate annual welfare loss at 2–6% of Ukraine's GDP highlighting previously ignored externalities of large-scale catastrophes.

1. Introduction

The past 60 years have witnessed 25 serious civic nuclear accidents, the gravest of which were Three Mile Island, Chernobyl and Fukushima.[3] Such low-probability high-loss events and their consequences represent negative externalities of energy production and use. However, assessing these externalities is complicated as our understanding of the potential societal and economic costs of large-scale disasters is limited. On the one hand, technological catastrophes involve direct explicit costs for recovery work, disaster relief, and monetary compensation for

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[3] These are according to the International Nuclear Event Scale 4–7: Chalk River 1952 (USA), Kyshtym 1957 (USSR), Sellafield 1957, 1973 (UK), Los Alamos 1958 (USA), Simi Valley 1959 (USA), Idaho Falls 1961 (USA), Charlestown 1964 (USA), Monroe 1966 (USA), Lucens 1969 (Switzerland), Rocky Flats 1969 (USA), Leningrad 1974 (USSR), Belojarsk 1977 (USSR), Bohunice 1977 (CSSR), Three Mile Island 1979 (USA), Saint-Laurent 1980 (France), Chernobyl 1982, 1986 (USSR, nowadays Ukraine), Buenos Aires 1983 (Argentina), Wladiwostok 1985 (USSR), Goiânia 1987 (Brazil), Sewersk 1993 (Russia), Tokaimura 1999 (Japan), Fleurus 2006 (Belgium), and Fukushima 2011 (Japan). The International Nuclear Event Scale by the International Atomic Energy Agency (IAEA) is an internationally recognized tool to communicate the safety significance of events involving nuclear radiation. The scale uses numerical ratings: 1 “Anomaly”, 2 “Incident”, 3 “Serious incident”, 4 “Accident with local consequences”, 5 “Accident with wider consequences”, 6 “Serious accident”, 7 “Major accident”. All levels above 3 are considered nuclear accidents. The only accidents in level 7 have been Chernobyl and Fukushima.

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victims. These costs are generally borne by the public as part of an implicit national insurance policy, because catastrophic events are hardly insurable. On the other hand, such disasters can induce higher order impacts and large implicit costs which have been mostly ignored in conventional economic and risk analyses.

In this paper we evaluate the long-run toll taken by a large-scale technological disaster on well-being, mental health and aggregate welfare. To date, these higher order effects have not been assessed in a representative, long-term setup. Our empirical analysis is based on the biggest nuclear accident on record: The Chernobyl disaster of April 26, 1986. It is among the most costly technological accidents and has triggered significant public health concerns. Ukraine's government spending to alleviate the consequences of Chernobyl, including clean-up, recovery work and liquidator[4] compensation, is estimated at USD 148 billion for 1986–2015 or 5–7% percent of annual GDP (in real terms as of 1992; Oughton et al. 2009).[5] While the largest cost share initially accrued to clean-up, resettlement and capital investments, more than 80% of contemporary expenditures relate to social benefits (Oughton et al. 2009).

Most of the early medical research and public attention was drawn to physical health consequences. However, except for the most severely affected clean-up workers and children, researchers could not unambiguously substantiate any adverse physical health effects in the low-dose population (UNSCEAR 2008). Yet, even 20 years after the accident the Ukrainian population reports poorer subjective health which is in obvious contrast to objective measures (Lehmann and Wadsworth 2011). This divergence between objective and subjective disaster related morbidity hints at psychological effects. In particular, humans dread disasters involving toxic exposure for their catastrophic and uncontrollable potential health impacts and for their contamination which is undetectable by human senses (Slovic 1987). Anxieties in the aftermath of nuclear accidents may have adverse mental health consequences (Bromet et al. 2011). This is highly relevant for public policy as reduced mental health in general and depression in particular are among the most important determinants of mortality, reduced productivity and low quality of life (European Commission 2004; WHO 2005).[6] However, no study has assessed the causal second order effects of a nuclear accident on the low-dose population (i.e., those affected by subclinical radiation doses). Such a long-term evaluation of mental health effects could not only improve our understanding of the implied aggregate welfare loss, but also contribute to the appraisal of nuclear accidents for public policy.

This paper provides the first empirical assessment of the psychological long-term implications of the Chernobyl catastrophe for the lives of the vast majority of Ukrainians for whom the disaster was—technically speaking—a low-exposure catastrophe. We deliberately exclude the small fraction of the population that received high levels of radiation and attracted most of the previous academic attention. Instead, we focus on the 96% of the population for whom the average additional radiation received in the first eight months after the disaster equaled half the annual dose of natural background radiation in Ukraine. This additional dose is low and comparable to 10 medical chest X-rays. Our paper makes three contributions: First, we exploit the natural experiment implied by the random variation in radioactive fallout to establish the causal link between the Chernobyl disaster and its impact on mental well-being. We match geographic variation in post-accident radiation doses of iodine-131 and caesium-137 with large-scale, representative survey data containing information on individual place of residence in the year of the disaster. Mental well-being is measured 20 years after the catastrophe with the following indicators: life satisfaction, diagnosed depressions and subjective survival probabilities. It is important to note that our research differs from the literature on the negative "news effect" of catastrophes on subjective well-being, which tends to measure transitory short term distress (e.g., Berger 2010; Kimball et al. 2006; Metcalfe et al. 2011). Second, by focusing on long-term mental health outcomes in the low-dose population we dissect a previously ignored welfare component of catastrophes. We compute the monetary equivalent of the aggregate welfare loss using the life satisfaction approach. This method has been used in the economics literature to evaluate the compensating differential for negative life events or environmental conditions (e.g., Clark and Oswald 2002; Frey et al. 2010; Levinson 2012; Lüchinger 2009; Lüchinger and Raschky 2009; van Praag and Baarsma 2005; Winkelmann and Winkelmann 1998). We further apply the method to estimate the value of a statistical life year from the perceived risk of premature death. Third, we complement the welfare analysis by highlighting another possible externality of the disaster, namely the greater reliance of individuals on government transfers as a source of livelihood.

Our results indicate, first, that even sub-clinical radioactive exposure has a significant and considerable negative effect on subjective well-being and mental health 20 years after Chernobyl. These results are surprising as they can be neither caused nor explained by actual physical health impairments. According to our estimates, one additional dose of natural background radiation leads to a reduction of subjective well-being by 20% of a standard deviation. This result proves robust to several sensitivity checks and the use of an objective depression indicator. Our findings on significantly reduced subjective survival probabilities furthermore suggest that worries about future individual health are one possible transmission channel through which the catastrophe impacts mental well-being. Second, the annual aggregate welfare loss for the low-dose population equals 2.2–5.5% of contemporary Ukrainian GDP. These numbers add to Ukraine's current recovery, clean-up, and liquidator compensation costs of about 5–7% of GDP per year. Third, Chernobyl indeed increases the reliance on the state as provider of subsistence. Affected working-age adults are more dependent on governmental social transfers; the fiscal equivalent of these additional benefits amounts to 0.5–0.6% of annual GDP.

Our findings have important implications for public policy: The psychological effects of a nuclear catastrophe are large and persistent, even for those exposed to extremely low, subclinical radiation doses. This matters because mental health is considered crucial not only for personal well-being and public health but also for productivity and economic growth (WHO 2013). Furthermore, the overall welfare loss is substantial and must be interpreted as an externality of nuclear electricity production. The explicit and implicit costs of large nuclear accidents can easily exceed the fiscal latitude of single states.

The remainder of the paper is as follows. Section 2 provides background information on the Chernobyl disaster and its consequences. Section 3 describes and discusses the identification strategy, the data sets as well as the methodological approach. This is followed by the empirical results for different mental well-being measures and one potential transmission channel in Section 4. This section also contains a discussion of the findings and further evidence on behavioral implications. Section 5 presents the monetary evaluation of the aggregate welfare loss caused by Chernobyl. Section 6 assesses the value of a statistical life year from the perceived risk of premature death due to Chernobyl. Section 7 concludes.

2. Background

2.1. The Chernobyl accident and its consequences

The meltdown and explosion of reactor 4 of the nuclear power plant in Chernobyl on April 26, 1986 (located in northern Ukraine) resulted in

[4] The clean-up workers assigned to deal with consequences of the Chernobyl disaster were called liquidators.

[5] The direct costs associated with the Three Mile Island (1979) accident range between 1–3 billion USD for the first decade (Faure and Skogh 1992). Note, the paper does not clarify whether these dollar amounts are nominal or real.

[6] For instance, to foster awareness for mental disorders and improve mental health care around the globe the WHO set up a Mental Health Action Plan (WHO World Mental Health Survey Consortium 2004).

the biggest civil nuclear accident on record.[7] The released radioactive matter formed a cloud that contaminated substantial areas of Belarus, Ukraine, and western Russia with radioiodine-131 and radiocaesium-137. In Ukraine, local wind direction, rainfall patterns as well as surface structure scattered radioactive fallout across tens of thousands of square kilometers, leading to regionally dispersed and unpredictable contamination levels (Fig. A-1 in the Appendix). Due to atypically strong eastern winds, vast areas of western and northern Europe were affected, too. The Chernobyl catastrophe was an exogenous and unanticipated event that impacted the population in a non-selective manner. Contamination was not a monotonic function of distance to the damaged power plant (Lehmann and Wadsworth 2011). These particular features of the Chernobyl disaster form the basis for the identification strategy of this paper.

In the vicinity of the reactor, where radioactive exposure was most harmful, fire-fighters, military personnel and recovery operations workers (so-called liquidators) tried to curtail the disaster[8]; several thousand people living in the reactor's immediate neighborhood were evacuated days after the accident and more than 100,000 residents were resettled from inside a 30-km zone of alienation in the following months. The humanitarian consequences of the disaster have been fiercely debated: While the official death toll is 'only' 30 (UNSCEAR 2008), several hundred thousand people were exposed to high radiation doses of 175 to 3000 times the average natural background radiation (350–6000 millisievert, mSv) in the vicinity of the reactor.[9] According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the number of people seriously affected by Chernobyl up to the year 1989 amounted to 1.6 million (UNSCEAR 2000). As clean-up works were and are still ongoing, these numbers were rising over time (UNSCEAR 2008). By January 2004, the number of Ukrainian adults officially recognized as Chernobyl victims (implying special social benefits) exceeded 2 million, corresponding to about 4% of the Ukrainian population (State Statistics Committee of Ukraine 2004).

It is this particular highly affected subgroup on which the medical and economic literature has focused to date. Despite the unprecedented scale of the disaster it has proven difficult to identify causal physical health effects in adults, e.g., leukemia. The existing evidence remains mixed and inconclusive.[10] In contrast, scientists agree that Chernobyl is responsible for significant increases in the prevalence of thyroid cancer in highly affected children (Demidchik et al. 1999; UNSCEAR 2000). Similarly, there is consensus about the mental health consequences for the most severely affected: Non-representative and mostly small-scale epidemiological and psychological studies show mental health impairments among clean-up workers (Ivanov et al. 2001; Loganovsky et al. 2008), those still residing in highly affected areas (Viinamäki et al. 1995; Havenaar et al. 1997) and among those evacuated or resettled by the government (United Nations 2002). Symptoms attributed to the accident include headache, depression, and sleep disturbance (UNSCEAR 2000). Self-abandonment, feelings of helplessness and lethargy have been described as mental reactions to the uncertainty about one's own health status and the worries about suffering from cancer in the future (United Nations 2002). Suicide rates are significantly higher in the seriously contaminated population (Bromet and Havenaar 2007).[11] In a nationally representative study for Ukraine, economists Lehmann and Wadsworth (2011) find negative long-term effects of radiation exposure on subjective health but not on objective physical health.

2.2. Uncertainty and anxiety in the low-dose population

In contrast to the highly affected population, the radiation doses received by the low-dose population were negligible. The additional effective caesium-137 dose between May and December 1986 did not exceed 2.1 mSv in any area, and the average additional dose in that time period was 1 mSv (comparable to half the annual level of national background radiation). In comparison, a U.S. citizen moving from Florida to South Dakota will increase her annual background radiation dose by more than 8 mSv per year. We focus on this under-researched vast majority (96%) of the Ukrainian population. The state-of-the-art medical literature is explicit that such low radiation exposure is subclinical, i.e., it causes neither physical nor neurological damage (UNSCEAR 2000, 2008; for a review see Appendix B of this paper).[12] Yet, several small-scale and qualitative studies suggest that the low-dose population is scared of radiation and attributes a variety of health conditions to radioactive contamination (Lee 1996; UNSCEAR 2000).

What might have triggered the described anxiety and health worries of people affected by low, subclinical radiation doses? After the accident, two mutually re-enforcing sources of uncertainty put the population under distress: First, individuals were uncertain about their treatment state, i.e. their personally received level of irradiation, as radiation is invisible, taste- and odorless. However, the Soviet government initiated large-scale countermeasures intended to protect residents from radiation. These countermeasures were geographically highly correlated with actual radioactive fallout[13] and have signaled the spatial variation in contamination to the low-dose population. Individuals who actually received very low radiation levels have as a consequence interpreted the official security measures as a signal for serious radiation and health danger (Lee 1996: 301; UNSCEAR 2008). Second, the potential health consequences of the treatment were perceived as highly uncertain. This perception was triggered, on the one hand, by the distinctive features of nuclear radiation and, on the other hand, by the unavailability of reliable information regarding expected health consequences of radiation. Nuclear radiation is often considered slow poison and its consequences may remain latent for long periods of time. Hence, it is uncertain whether and when its consequences will be realized. The unresolved and sometimes ideologically motivated

[7] More detailed accounts of the timeline of the events as well as technical details can be found in the 1998 European Commission Atlas of caesium deposition on Europe after the Chernobyl accident (European Commission 1998), two United Nations reports from 2001 and 2002 (United Nations 2001, 2002), and two UNSCEAR reports from 2000 and 2008 (UNSCEAR 2000, 2008), as well as in a national report from Ukraine (Baloga et al. 2006).

[8] Military personnel and liquidators were deployed from various parts of the Soviet Union.

[9] Estimates of the expected long-run death toll vary vastly between 4000 (IAEA 2005) and almost 200,000 (Greenpeace 2006). This huge variance reflects and produces uncertainty about actual health effects.

[10] For instance, it is uncertain, to what extent increased cancer rates should be attributed to intensified health screening efforts in the aftermath of the catastrophe (United Nations 2002). Nevertheless, future health effects cannot ultimately be ruled out in case radiation exposure over long time periods has consequences which are unknown to date. One yet unresolved medical question is whether the latency period of radiation is much longer than previously assumed (i.e. much more than 30 years, so that health implications can only be measured in the future) (Pflugbeil et al. 2011). Some authors argue that genetic abnormalities might be discovered in descendants of strongly affected individuals only at a later stage (Baverstock and Williams 2006). Whether this might also apply for low-dose recipients has not been discussed in the literature.

[11] Note that Ukraine underwent serious economic restructuring and transition challenges after the breakdown of the Soviet Union. These shocks may have affected some of our outcome measures. However, the transition shocks were common to everybody, irrespective of exposure to Chernobyl.

[12] Different from previous assumptions, the U.S. National Academy of Sciences BEIR VII Committee (2006) now argues that the cancer risk may actually increase linearly, without threshold in radiation exposure. Strictly speaking, this implies the theoretical possibility that very low doses do affect the cancer rate, albeit at undetectable levels.

[13] The USSR Ministry of Public Health set up the Government Medical Commission (GMC) which decided on countermeasures based on Soviet safety standards developed in 1971 ("Criteria for decision making about population protection in case of a nuclear accident"). The initial measurement of radioactive fallout was performed by the meteorological service. The density of detector facilities was increased rapidly during the days following the onset of the disaster and data collection was especially intensified in more affected areas (Drozdovitch et al. 2013). A network of 1000 dosimetric control posts was established along transportation lines and in more affected areas, producing over 200 m measurements in populated areas in the first year after the accident. The resulting regional radiation concentration pattern guided the deployment of 2000 health teams set up by the GMC to provide prophylaxis and screen radiation in humans (Sergeev 1988).

scientific debate on long-term health outcomes, especially with respect to cancer in adults, fostered uncertainty. Additionally, the Soviet government deliberately concealed the scale and danger of the accident in 1986, which must have seemed at odds with the series of large scale countermeasures.[14] These contradictory signals created room for rumors and fear which further increased the perceived uncertainty in the population (Bromet 2012; Rahu 2003). Recent research on the role of risk communication in the aftermath of large-scale nuclear accidents seems to confirm that information can serve as a signal about disaster exposure. In fact, as shown for the accident of Fukushima in 2011, less credible information and greater uncertainty about the consequences of the disaster led to elevated levels of distress in Japan (Rubin et al. 2012).

The most salient disaster exposure signals received by ordinary citizens were the distribution of Potassium Iodide prophylaxis to saturate the thyroid gland with non-hazardous iodide (Mettler et al. 1992), the introduction of a compulsory Chernobyl registry in mid-1986 involving annual medical examinations across the more affected areas (UNSCEAR 2000: 490), the collection of several hundred thousand thyroid measurements and blood tests which had much better coverage in more affected areas (Likhtarev et al. 1994), the setting up of several international medical projects with (partly mobile) cancer screening facilities between 1986 and 1996[15] which gave rise to rumors about disastrous health consequences (Baloga et al. 2006; Gould 1990), and, finally, the widespread screening measures for locally (and even privately) produced food, milk and dairy products as vast tracts of land became unusable for agricultural production (Firsakova 1993; Likhtarev et al. 1994; UNSCEAR 2008: 74).[16] These countermeasures varied at the regional, not individual, level. Anecdotal evidence suggests that the authorities intensified and scaled-up local countermeasures once higher radiation levels were found on the ground. This is true for blood and thyroid screening programs (Stepanova et al. 2008), which were later incorporated in the All-Union Dose Registry. Similarly, iodine prophylaxis was initially only intended for the personnel of the nuclear power plant and residents of the nearby town Pripyat; however, the scale of iodine prophylaxis was soon geographically expanded to cover more and more areas with radioactive fallout. Finally, more than 5.4 million individuals were treated (Kondrusev 1988). To counter the fears of the low-dose population in areas with elevated radiation level, more than 3000 public discussions and hearings about radiation protection were carried out alone in 1986 by "mobile agitating teams" (Kondrusev 1988: 45).

2.3. Mental long-term effects of disasters

The medical literature has documented mental long-term effects of a variety of natural disasters and man-made catastrophes (Logue et al. 1981; Bland et al. 1996; Norris et al. 2002a). Comprehensive review articles by Norris et al. (2002a) and by Norris et al. (2002b) suggest that mental stress can be quite enduring and potentially more persistent than physical health problems. It can be accompanied by 'psychic numbing' (Logue et al. 1981). Especially serious mental health consequences can be expected from disasters that affect individuals randomly and uncontrollably by creating acute helplessness and anxiety. Yet, previous medical and psychological studies are limited in that they (1) focus almost exclusively on strongly affected individuals; (2) mostly concentrate on relatively short post-disaster periods of only 2 to 7 years; and (3) hardly ever use large or even (nationally) representative data.

The mental toll of Chernobyl in the low-dose population has rarely attracted scientific attention. A recent qualitative study with 30 informants showed that even physically healthy individuals tend to be afraid of cancer or genetic defects in their children (Abbott et al. 2006). A comparative study between highly affected and hardly affected areas in Belarus seven years after the disaster found only small differences because the incidence of mood and anxiety disorders was very high in the control region (Havenaar et al. 1997). Some physicians have coined the term 'Chernobyl disease' for unexplained physical symptoms such as headache, fatigue, dizziness or sleeplessness in the low-dose population (WHO 2006).[17] These have been first attempts to understand mental health problems among recipients of low radiation doses; in the following we provide the first comprehensive assessment.

3. Methodology and data

3.1. Identification strategy

This paper exploits regional variation in radioactive fallout levels to study the effect of a large-scale catastrophe on long-term mental well-being and behavioral outcomes. In effect, we compare individuals who had been relatively more or less exposed to the disaster according to their place of residence in 1986. We use a representative survey of the Ukrainian population and focus on the 96% of the population that was randomly affected by different levels of subclinical radiation doses and that was neither resettled nor involved in disaster liquidation. It is important to stress that we do not interpret our findings on mental well-being as causal effects of radioactive contamination itself. Rather, our estimates represent significant psychological long-term disaster effects: the population received information signals about their likely treatment status from countermeasures which had been taken by the authorities in order to prevent the absorption of radiation. The intensity of these countermeasures (signals) was regionally highly correlated with actual radioactive fallout.

Undoubtedly, the Chernobyl catastrophe was an unanticipated accident and created an unexpected pattern of regional radiation levels due to unforeseen weather and wind conditions. However, for the regional variation to serve as a valid quasi-experiment, we need to be sure that radiation levels are not correlated with possibly confounding differences in the regional characteristics of the population. One possible confounding effect could be selection into treatment created through endogenous location choice of individuals and families in 1986, that is, if certain types were more likely to live in close proximity to potentially harmful sources like nuclear power plants.[18] We argue that this possibility does not apply in our set up: Since the risks of the civil use of nuclear power were generally less well understood at that time, the population's settlement choices were unlikely to be endogenous. More importantly, residential mobility was severely restricted in the Soviet Union,[19] a country particularly secretive about strategically important sites. Furthermore, contamination was not a monotonic function of distance to Chernobyl (Lehmann and Wadsworth 2011).

Another possible threat to the identification strategy could be endogenous radiation exposure through selection into clean-up work

[14] See Chapter 1 in Baloga et al. (2006).

[15] The Chernobyl project (1990–1), the IPHECA project (1992–5) and the Chernobyl Sasakawa Health and Medical Cooperation Project (1991–6).

[16] The contaminated area in Belarus, Ukraine, and Russia totalled 784,000 ha of agricultural land and 694,000 ha of forest (United Nations 2002), equivalent to the size of Kuwait and larger than the state of Connecticut. In Ukraine, the contaminated area represents 2% of arable land (Bouzaher et al. 1994).

[17] These negative psychological consequences might be comparable to so-called nocebo effects. While a placebo effect is defined as beneficial reaction to an ineffectual medical substance (simulated treatment), a nocebo effect is defined as a negative reaction to such an ineffectual treatment (Hahn 1997).

[18] In our sensitivity analysis, we control for living nearby an active nuclear power plant. As of 1986, there were four active nuclear power plants in Ukraine, which were scattered across the country: Rivne (North–West), South Ukraine (South), Zaporizhzhia (East) and Chernobyl (North). A new plant (Khmelnitsky, Centre-West) opened in 1987, while all Chernobyl reactors were finally shut down by the time of the ULMS interviews.

[19] Individuals' labour market choices and mobility were limited due to the internal passport system as well as to the administrative allocation of housing during the Soviet Union (Gregory and Kohlhase 1988).

and possibly selected mortality. Indeed, although the deployed liquidation workers were not volunteers, they might differ from the low-dose population as they were predominantly drawn from military, emergency and technical occupations. These workers were exposed to high—some of them to lethal—doses of external radiation and received special medical treatment and attention (e.g., in the form of welfare supplements) (Lehmann and Wadsworth 2011). To account for this problem, we exclude from our sample all evacuees from within the 30-km exclusion zone and later-resettled populations as well as all persons involved in the recovery works.[20] Hence, our analysis will provide conservative estimates and underestimate the overall (mental) health costs of the disaster.

3.2. Data and main variables

Our estimation of the long-term effects of the Chernobyl catastrophe makes use of the Ukrainian Longitudinal Monitoring Survey (ULMS), a rich nationally representative panel data set.[21] These data are unique in providing, on the one hand, information on mental well-being 20 years after the accident and, on the other hand, retrospective information on place of residence at the time of the accident as well as on individual-level involvement in clean-up work and resettlement. The panel survey was carried out in the summer months of 2003, 2004, and 2007 by the Kiev International Institute of Sociology (KIIS) and included more than 6000 adults aged 15 to 75 (Lehmann et al. 2012). The survey contains an individual questionnaire on socio-demographic characteristics, labor force participation, subjective well-being, attitudes, and health status, as well as a household questionnaire focusing on household composition, income, and housing. A pivotal feature of the ULMS is its collection of retrospective labor market and residential history starting in 1986—the year of the Chernobyl catastrophe. Although recall periods are long, the retrospective information is considered reliable due to the fact that the survey employed memory-anchor techniques and exploited information registered in official Soviet work books whenever available. Exact location of respondents' place of residence in 1986 is crucial for mapping nuclear radiation doses to individuals. We restrict the sample to individuals born before April 26, 1986—this excludes children *in utero* during the accident, since Almond et al. (2009) demonstrate that prenatal exposure was potentially harmful.[22,23] After excluding the potentially selectively assigned clean-up workers and the resettled population, the final sample comprises 11,922 person-year observations.

We additionally exploit another large Ukrainian micro data set containing information on diagnosed mental health conditions: the Ukrainian Household Budget Survey (UHBS), conducted by the Ukrainian Statistical Committee. This annual cross-sectional survey collects household- and individual-level information for around 24,000 individuals in about 9500 households in December of each year. Mental health (i.e., a mental disorder diagnosed by a physician) was covered in the years 2004 to 2006, yielding a sample size of more than 44,000 observations for the analysis. The drawback of the UHBS data is that they lack information on place of residence as of the year 1986 and that we have to assign radiation doses to current place of residence. To address this problem in the UHBS analyses, we reweigh the radiation doses by the inter-regional migration matrix between 1986 and 2003 and additionally control for the inter-regional mobility over the same time period.[24] To assure comparability between the two data sets, we restrict the UHBS sample to respondents born before the accident and not older than 75 years at the time of the interview.[25]

3.2.1. Measures of the disaster effect

To measure the impact of the disaster, we use official regional radiation data that we match to individuals based on their place of residence in the year 1986.[26] We focus on average effective total exposure doses of caesium-137, reflecting the energy absorbed by matter (measured in millisieverts, mSv). This is the preferred measure for gauging any long-term (biological) impact, since it allows combining internal (through ingestion and inhalation) and external (fallout) radiation doses. It matters because household farming was an important source of subsistence in the Soviet Union (Baloga et al. 2006). As stated above, the received doses in our study population are low and amount on average to 1 mSv for May–December of the year 1986. This is comparable to half the natural annual background radiation in Ukraine. As additional radiation measure for children, we use regional average exposure to iodine-131. Children and adolescents have been especially vulnerable to this radioactive isotope (owing to common iodine deficiencies) and were subsequently more prone to suffer from thyroid cancer.[27] Hence, affected children might suffer from an increased perceived risk or worries about future illness. Among the most affected children in our sample, the iodine-131 doses (measured in milligray, mGy) were the equivalent of about 100 abdominal X-rays for adults.[28]

We use official measures on regional averages in radiation exposure provided in Baloga et al. (2006).[29] The radiation data stem from measurements at various locations and are then averaged and extrapolated to larger areas (610 districts with on average 75,000 inhabitants). Specifically, caesium-137 estimates are based on 30,000 white blood cell (WBC) measurements in 1986 across rural and urban locations in Ukraine. Average regional absorbed thyroid doses are estimated based on 150,000 direct measurements of radioiodine activity in the thyroid gland of individuals living in contaminated regions (Baloga et al. 2006). The resulting regional radiation measure is relatively crude and might hide intraregional variation.

3.2.2. Mental well-being indicators

The main dependent variable in our assessment of the impact of Chernobyl on individual mental well-being is general life satisfaction. While economic studies interpret subjective well-being as a proxy for utility or welfare (see, e.g., Clark et al. 2008), medical psychologists understand it as affective construct that can be used to assess mental health in general (Headey et al. 1993) or as indicator for clinical depression in particular (Gargiulo and Stokes 2009). One important assumption for using subjective well-being is that we can compare it across respondents. While some economists are skeptical about subjective well-being measures, others defend the approach and highlight its

[20] Our data set contains indicators on whether individuals took part in the liquidation process (1.6%) or were evacuated or resettled due to the Chernobyl catastrophe (1.2%).

[21] Note, that the use of a panel is not pivotal for our identification strategy. We show our main results using the entire panel to improve precision and to more easily compare our results to Lehmann and Wadsworth (2011). Our estimates remain significant in a cross-sectional set-up (Table A-8).

[22] Our results are robust to including children *in utero* at the time of the catastrophe (results not shown).

[23] Similarly, negative effects of *in utero* exposure to low-dose nuclear radiation are also found by Black et al. (2013) for Norway as well as Halla and Zweimüller (2014) for Austria.

[24] The formula is $Radiation_k = \sum m_{j8603} \times Radiation_{j86}$, with m denoting the 2003 population fraction of region k originating from region j as of the year 1986. The full inter-regional migration matrix is based on official migration data from the State Statistics Committee of Ukraine.

[25] As in the ULMS, we also exclude the most severely affected individuals. After applying these sample restrictions, the two datasets are very similar with respect to standard socio-economic characteristics.

[26] This procedure has also been carried out by Lehmann and Wadsworth (2011). However, in contrast to us, they assign a measure of surface contamination with caesium-137 measured in kilobequerels per square meter (kBq/sqm) to each individual. Furthermore, individuals who did not live on Ukrainian territory in 1986 (4.5% of the sample) were assigned zero exposure doses (none of these individuals originated from affected areas of Belarus or Russia). The results are robust to either assigning the minimum radiation value of the sample or omitting these observations (results not reported).

[27] While caesium-137 has a relatively long half-life of 30.8 years, iodine-131 has a half-life of about eight days.

[28] Milligray is a measure of the absorbed dose.

[29] Data are taken from the official report “20 Years After Chernobyl Catastrophe. Future Outlook: National Report of Ukraine,” Tables 3.3.7 and 3.3.9 (Baloga et al. 2006, pages 45, 47, 48).

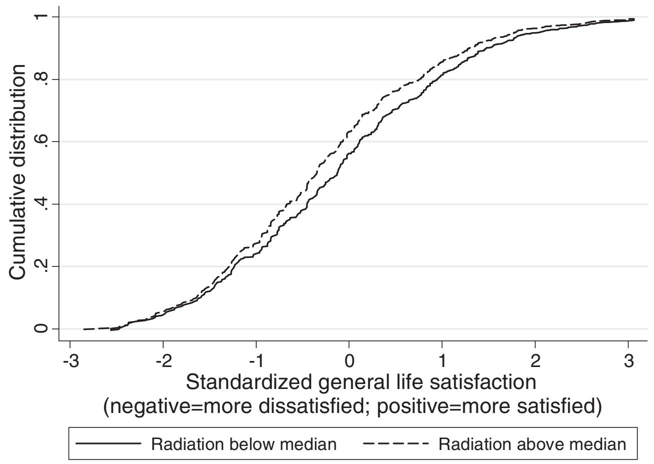

Fig. 1. Cumulative distribution of life satisfaction. Source: Conditional distribution, controlling for age and time fixed effect, ULMS 2003–2007, number of observations: 11,922; own calculations.

advantages (Ng 1997; Frey and Stutzer 2002; Levinson 2012). Furthermore, subjective well-being tends to correlate with objective measures and has passed a series of reliability tests (Frey and Stutzer 2002).

Our subjective well-being indicator is measured on a five-point Likert scale from *fully dissatisfied* (1) to *fully satisfied* (5) and is based on the ULMS question: "*To what extent are you satisfied with your life in general at the present time*?" The mean level of life satisfaction is 2.59 (with a standard deviation of 1.16). A first glance at the data reveals that individuals who resided in areas exposed to above median radiation report lower levels of life satisfaction (Fig. 1).

As an alternative measure, we collapse the five-point life satisfaction variable into a binary dependent variable (*unhappy*), identifying all individuals who answered being fully dissatisfied with their life (21% of the sample). In addition, we use two further dependent variables: The first is a binary variable indicating whether the respondent has been diagnosed for six months or longer with *depression or chronic anxiety* (UHBS data). The second dependent variable is *subjective survival probability* which is based on a question covered in the ULMS wave 2007. Individuals aged 46 and above were asked to rate the probability that they will survive until a certain target age in the future.[30] This target age is 65 for all respondents aged 46 to 55, 70 for those aged 56 to 60, 75 for those aged 61 to 65, and 80 for those above 66. If Chernobyl increased individual worries about future adverse health outcomes and lowered mental well-being, we expect more affected persons to report lower subjective survival probabilities.

3.3. Estimation strategy

We estimate the long-term effects of the Chernobyl catastrophe on standardized mental well-being and other outcomes y of individual i living in region k (26 oblasts) at time t:

$$y_{ikt} = \beta_0 + \beta_1 Radiation_{j86} + X'\gamma + \tau_k + \sigma_t + \theta_m + \varepsilon_{ikt}. \quad (1)$$

Radiation is the objectively measured average exposure dose that respondents received according to their region of residence j_{86} in 1986. For ease of interpretation we express the radiation measure in terms of units of natural background radiation. The coefficient of interest is β_1, which measures the impact of one unit of natural background radiation on our outcome measures y. Long-term negative psychological effects of the Chernobyl catastrophe would yield a negative $\hat{\beta}_1$. Without adding further controls for potential channels to the regressions, $\hat{\beta}_1$ should capture the gross reduced form long-term effect of the nuclear accident on today's mental well-being. However, to account for possible channels through which Chernobyl might have affected long-term well-being, different sets of control variables are included in X one after the other. Initially, predetermined personal characteristics (gender and age[31]) are added to the regressions. This is followed by education and marital status, as well as proxies for the physical health status of individuals.[32] For the regressions concerning depression (UHBS), we control for regional doctor contact rates to account for the heterogeneity in access to health care.[33] We also add a set of dummy variables for current labor force participation status, household size, log of household income, living space per capita as a proxy for permanent income or wealth and settlement type (village, town, or city). If these sets of variables reflected different transmission channels, their inclusion should gradually reduce the overall size of the $\hat{\beta}_1$ coefficient. Furthermore, after controlling for these various channels, the $\hat{\beta}_1$ coefficient represents the long-run effect of the catastrophe *conditional* on individual coping and adaptive behavior that could have either mitigated or exacerbated the Chernobyl effect. All regressions control for administrative region k, year t, and month of interview m fixed effects. ε_{ikt} is an iid error term. Standard errors are clustered at the j_{86} level.[34] Variable definitions and descriptive statistics of all variables are provided in Tables A-3 and A-4.

We estimate Eq. (1) with OLS. While OLS estimates are intuitive to interpret and are consistent under classical assumptions, they do not account for the categorical character of the dependent variable (and are therefore less efficient). As sensitivity tests we re-estimate our main models with ordered probit, interval regression, random effects GLS, probit and linear probability methods. Note, that we use repeated observations from the same individuals over time to yield greater precision. Hence, our main result reflects the average effect across survey waves; however, our results are preserved if we used single cross-sections (Table A-8). To account for potential endogeneity and measurement error in household income we apply instrumental variable methods (see Section 5).

4. Results: long-term effects of the Chernobyl disaster on mental well-being

As a first assessment, we compare means of the most relevant variables between individuals who lived in areas with above vs. below median radiation doses in 1986. We condition these means on region (oblast) and age because the regional age composition differed across Ukraine prior to 1986 owing to rural to urban migration in the 1960s and 1970s (Feshback 1985) and because inter-regional migration (between more and less affected regions) has affected the intra-regional age and radiation distribution[35]: Clearly, the treatment proxy (radiation dose) and the outcome variable are significantly different between the

[30] There are 1958 observations in the estimation sample for which this variable is non-missing. The mean of this variable is 53.9% (standard deviation of 27.0).

[31] While the literature has often assumed a u-shaped pattern between age and subjective well-being, we allow for greater flexibility by using age fixed effects. However, our results remain virtually unchanged if we, like other researchers, apply linear, quadratic, or cubic age specifications (Blanchflower and Oswald 2008). Our results are also robust to controlling for the natural logarithm of age in order to account for the subjective feeling that time passes more quickly as individuals age (van Praag and Baarsma 2005) (see Appendix, Table A-5).

[32] The health measures are (1) a dummy variable for having at least one of seven different chronic physical diseases (*chronic*: heart disease, illness of the lungs, liver disease, kidney disease, gastrointestinal disease, spinal problems, or other chronic illnesses) and (2) the individual's height (*height*). We also add measures of risky behaviour (*smoking* and *drinking*).

[33] This variable is defined as the fraction of individuals having accessed medical services (doctor or hospital) in one of 77 sub-regions (defined by oblast and settlement type city/town/village) during the past year.

[34] Applying two-way clusters (by region j_{86} and personal identifiers) increases the standard errors by less than 5%.

[35] Movers are typically younger and better educated individuals; however, migration (and controlling for migration) does not affect our results (Table A-11).

Table 1
Descriptive statistics of areas with above vs. below median radiation.

	Above radiation median	Below radiation median	Difference	S.E.	T-stat
Radiation (in natural background units)	0.704	0.243	0.461	0.091	5.1***
Life satisfaction	2.561	2.627	−0.066	0.021	−3.1***
Male	0.373	0.429	−0.056	0.046	−1.24
Age‡	45.702	45.618	0.084	0.102	0.83
Height	167.525	167.874	−0.349	0.744	−0.47
Years of schooling	11.937	11.852	0.085	0.071	1.19
Married	0.731	0.682	0.049	0.041	1.21
Widowed	0.088	0.087	0.001	0.007	0.16
Separated	0.076	0.102	−0.026	0.027	−0.99
Unemployed	0.068	0.070	−0.002	0.015	−0.16
Pensioner	0.243	0.244	−0.001	0.008	−0.17
Inactive	0.153	0.154	−0.000	0.021	−0.01
Chronic disease	0.581	0.545	0.036	0.025	1.44
Drink alcohol	0.453	0.466	0.024	0.027	0.93
Smoking	0.272	0.303	−0.031	0.025	−1.25
Household size	3.402	3.324	0.078	0.082	0.95
Log(income)	6.552	6.496	0.056	0.043	1.31
Log(living space pc)	2.356	2.230	0.126	0.104	1.21
Rural	0.341	0.337	0.004	0.005	0.89

Note: Number of observations: 19,222. The two groups have been balanced by age and region, as differences in the age composition of regions existed prior to the Chernobyl disaster. The difference of the mean comparison is the β_1 from the following OLS regression: $Y=\beta_0+\beta_1 \text{abovemediandose}+\sum\beta_a \text{age}_a+\tau_k+\varepsilon$, where age_a are age dummies. Robust standard errors clustered by region of radiation in parentheses. ‡The means comparison of age is balanced only on regions. *** $p<0.01$. Source: ULMS 2003-2007; own calculations.

two groups (Table 1) with expected signs. Exogenous variables such as gender and height as well as potentially endogenous individual or household characteristics are not significantly different, often with tiny absolute differences. This comparison supports our presumption that, conditional on age and region, residents of more and residents of less affected areas were highly comparable.

Furthermore, regions which received different levels of radioactive fallout in 1986 were structurally similar at the time of the accident. In a series of individual and regional level regressions we show that there were no significant differences between more and less affected areas with respect to pre-determined characteristics such as educational attainments, employment rates, wages, wage growth, or emigration rates (see Appendix, Tables A-1 and A-2).[36]

Regressions confirm that greater disaster impact reduces contemporary well-being even 20 years after Chernobyl: The effect associated with an increase of one unit of natural background radiation reduces life satisfaction by 18% of a standard deviation (Table 2). Recall, that the actual average radiation dose for the low-dose population in 1986 was about half a dose of natural background radiation. Against the background of such a virtually ineffectual treatment, the long-run disaster effect seems large. Adding predetermined demographic characteristics (age and gender) reduces the size of the estimated effect only marginally (Column 2). In general, men seem to be significantly more satisfied with their lives than women (however, the gender coefficient becomes smaller and insignificant once further controls are included in the estimation). Column 3 includes all other individual and household level controls. Being married, having acquired more years of schooling, as well as generating higher household income are associated with higher levels of life satisfaction—in line with the large literature on subjective well-being.[37] For instance, our income coefficient compares well to the estimate in Frijters et al. (2004) using German data.[38] However, we acknowledge that household income is potentially endogenous.[39] This problem will be addressed when calculating the monetary equivalent of the aggregate welfare loss from Chernobyl (Section 5). Persons suffering from chronic illnesses have a lower life satisfaction than healthy persons. The coefficient of being unemployed is sizeable and more than twice as large as the coefficient on bad health—similar to the previous literature (Winkelmann and Winkelmann 1998). However, despite controlling for these potential channels, the coefficient of the radiation variable remains remarkably stable across all specifications. This is in line with prior evidence that higher radiation levels did not affect physical health—and labor market outcomes of the strongly affected only to some limited extent (Lehmann and Wadsworth 2011). Our results suggest a significant and long-term negative effect of the Chernobyl catastrophe on subjective well-being. We thus add to the existing post-disaster literature (Norris et al. 2002a, 2002b) by establishing typical post-disaster mental health problems for (i) a truly low-affected population (ii) in the very long-run (iii) with a large nationally representative sample. This effect holds equally for men and women.[40] The same is true when running separate regressions for children aged zero to 18 at the time of the disaster and adults. Column 6 of Table 2 shows qualitatively identical results when using information on absorbed doses of iodine-131 by children as alternative measure for radiation exposure. When we standardize radiation exposure (mean 0, std. 1) for better comparability, the effect of an increase of one standard deviation of radiation on life satisfaction is remarkably similar for caesium-137 (−0.076) and iodine-131 (−0.066) (reported at the bottom of columns 5 and 6). Given that the potential health threat from I-131 was a multiple of that from C-137, and given that the half-life of caesium is 1400 times longer than that of iodine, the similarity of results suggests that the disaster effect is indeed a fear effect.

The results are robust to alternative estimation methods[41] (Table A-7) and to estimating separate regressions for each survey wave (Table A-8). Note, that the persistence of the significant Chernobyl effect across years and its significance in the pooled model counter one often articulated critique that subjective well-being may exclusively capture emotional affect at the survey date. The point estimate of the disaster effect seems to gradually decline over time; however, the differences between waves are not statistically significant at conventional levels. To test whether our results are driven by one single (most affected) region, we repeat the analysis excluding each of the seven most affected regions one at a time (Table A-9 in the Appendix). Again, the results remain very similar. We show that radiation is not a monotonic function of distance to Chernobyl and that distance does not even partially explain our results (Appendix C). We also demonstrate that our results are not confounded by respondents who used to live in 1986 or currently live close to an active nuclear power plant by adding a dummy variable indicating the presence of a nuclear power plant in the region of residence and its interaction with radiation (Table A-10 in the Appendix).

[36] Unfortunately, there are no pre-1986 data sets containing subjective/mental well-being and regional indicators for the Ukrainian Soviet Socialist Republic. When assessing the cross-regional mobility patterns of the non-resettled low-dose population between 1986 and 2003 with the ULMS data, we find no significant correlation between the average radiation dose and subsequent outward mobility of a region. Hence, low radiation doses seem not to have induced sorting across regions. Furthermore, less than 1% of those who changed residence between 1986 and 2003 related the move to the Chernobyl catastrophe (according to the detailed ULMS migration module). Controlling for movers does not change the results (Table A-11).

[37] We have also added income separately to the specification in column 2. This does not alter the estimated disaster effect.

[38] Since their estimate refers to an 11-point-scale life satisfaction variable, we rescale our estimates.

[39] Note that other variables are potentially endogenous, too: marital status, risky behavior etc. The literature, however, is ambiguous as to whether marriage, divorce, or risky behavior decrease or increase as a consequence of stress. Lehmann and Wadsworth (2011) find no significant effects of Chernobyl on these outcomes (with the exception of a negative effect on the number of smoked cigarettes).

[40] See Table A-6 in the Appendix.

[41] The marginal effects for the five different satisfaction outcomes in the ordered probit model show that higher radiation significantly increases the probability of reporting lower levels of life satisfaction and decreases the probability of reporting higher levels of life satisfaction. The marginal effects from the probit regressions (dependent variable *unhappy*) imply that one unit of background radiation increases the likelihood that individuals are unhappy with their life by about 10 percentage points.

Table 2
The long-run effect of Chernobyl on life satisfaction.

Sample	(1)	(2)	(3)	(4)	(5)	(6)
	Full	*Full*	*Full*	*Adults (aged 19+ in 1986)*	*Children (aged 0–18 in 1986)*	*Children (aged 0–18 in 1986)*
Dependent variable	*Life satisfaction*					
Radiation	−0.183***	−0.159***	−0.196***	−0.132**	−0.314***	
	(0.061)	(0.054)	(0.052)	(0.061)	(0.074)	
Radiation iodine-131						−0.010***
						(0.002)
Male		0.075***	0.028	0.046	0.037	0.038
		(0.016)	(0.027)	(0.028)	(0.060)	(0.060)
Married			0.229***	0.002	0.304***	0.300***
			(0.047)	(0.069)	(0.047)	(0.047)
Widowed			0.107**	−0.111*	0.215	0.212
			(0.050)	(0.063)	(0.255)	(0.255)
Separated			0.030	−0.177**	0.085*	0.085*
			(0.049)	(0.084)	(0.045)	(0.045)
Years of schooling			0.038***	0.036***	0.049***	0.049***
			(0.005)	(0.005)	(0.010)	(0.010)
Chronic			−0.217***	−0.230***	−0.189***	−0.187***
			(0.016)	(0.019)	(0.031)	(0.031)
Drinker			0.009	0.087	−0.235***	−0.231***
			(0.069)	(0.072)	(0.083)	(0.082)
Smoker			−0.084***	−0.099***	−0.062	−0.060
			(0.021)	(0.032)	(0.037)	(0.037)
Height			0.003*	0.002	0.003	0.003
			(0.001)	(0.002)	(0.002)	(0.002)
Unemployed			−0.491***	−0.433***	−0.558***	−0.557***
			(0.028)	(0.035)	(0.055)	(0.055)
Pensioner			−0.183***	−0.186***		
			(0.042)	(0.039)		
Inactive			−0.155***	−0.211***	−0.073	−0.072
			(0.034)	(0.039)	(0.055)	(0.055)
Household size			−0.014	−0.014	−0.012	−0.012
			(0.011)	(0.013)	(0.015)	(0.015)
Log income			0.152***	0.169***	0.124***	0.123***
			(0.016)	(0.020)	(0.021)	(0.021)
Space pc			0.037***	0.038***	0.027	0.027
			(0.010)	(0.012)	(0.021)	(0.021)
Region and settlement FE	✓	✓	✓	✓	✓	✓
Year and month FE	✓	✓	✓	✓	✓	✓
Age FE	–	✓	✓	✓	✓	✓
Effect of + 1 st.dev. in radiation	*(C-137)*	*(C-137)*	*(C-137)*	*(C-137)*	*(C-137)*	*(I-131)*
	*-0.042****	*-0.036****	*-0.045****	*-0.030***	*-0.076****	*-0.066****
Observations	11,922	11,922	11,922	8561	3361	3361
R-squared	0.081	0.121	0.200	0.184	0.200	0.200

Notes: Dependent variable is standardized with mean of zero and std. of one. Iodine-131 is measured in logs. Robust standard errors clustered by region of radiation in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1. Source: ULMS 2003–2007; own calculations. The regressions in columns 5 and 6 are based on the subsample of persons born after 1967 and before April 26, 1986.

Finding significant results after 20 years indicates that life satisfaction has not returned to its baseline, suggesting no full adaptation to the catastrophe. This is in line with recent economic studies on idiosyncratic strokes of fate (e.g., Oswald and Powdthavee 2008; Powdthavee and Stutzer 2014). Yet, the Chernobyl disaster differs from such shocks, since it has not significantly deteriorated the physical health of the population (Lehmann and Wadsworth 2011). Instead it raised the potential *risk* of and worries about adverse future health conditions due to an incurred but unspecific treatment. Our results, however, contrast evidence by Berger (2010) who could not substantiate a ‘news effect’ of Chernobyl on happiness for Germany in the short run (potentially due to confounding seasonality effects and/or differences in the magnitude of the treatment).[42]

4.1. Further evidence on objective mental well-being

Do the results on lower life satisfaction reflect poor mental health even in the Ukrainian low-dose population? We complement our analysis of subjective well-being by estimating the effect of Chernobyl on objective mental health outcomes using diagnosed depression and anxiety disorders in the nationally representative UHBS survey. Generally, the depression incidence rate in Ukraine (9%) is high by international standards and 7% of the population suffer from anxiety disorders (WHO World Mental Health Survey Consortium 2004). Overall, roughly 10–12% of the population suffer from at least one of these mental disorders (there is considerable overlap between the two). Yet, only 3% of the population are actually diagnosed by a physician with a mood or anxiety disorder (Wang et al. 2007), a number that matches the incidence rate in our data set (3% in UHBS). The vast majority of mental disorders remains undetected in developing and emerging countries, as service coverage remains poor (Bromet et al. 2011; Wang et al. 2007; WHO World Mental Health Survey Consortium 2004).

In Table 3 we present regression results where the dependent variable is a binary indicator for having been diagnosed with depression or chronic anxiety.[43] To identify individuals who have been affected by the Chernobyl catastrophe, we use objective radiation doses reweighted by the inter-regional migration matrix between 1986 and 2003. Alternatively, and as a robustness check, we use a binary indicator for Chernobyl exposure based on a subjective assessment of whether a

[42] Berger's study focuses on environmental concerns and happiness in Germany around the date of the Chernobyl disaster. She exploits variation in interview dates of the cross-section 1986 of the GSOEP data.

[43] Given that the diagnoses are self-reported, this variable might suffer from measurement error (e.g., through under-reporting due to stigma).

Table 3
The long-run effect of Chernobyl on diagnosed mental disorders.

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	*Depression or chronic anxiety*					
Radiation	0.013***		0.017***		0.015***	
	(0.002)		(0.002)		(0.003)	
"Affected by Chernobyl"		0.016***		0.014***		0.014***
(subjective measure)		(0.004)		(0.003)		(0.003)
Region and year FE	✓	✓	✓	✓	✓	✓
Full set of controls	–	–	✓	✓	✓	✓
Regional doctor contact rates	–	–	–	–	✓	✓
Observations	44,097	44,097	44,097	44,097	44,097	44,097
R-squared	0.002	0.002	0.011	0.011	0.011	0.011

Note: The mean of the dependent variable is 0.03. Linear probability estimations. Radiation is measured in units of background radiation. The subjective measure of having been hit by Chernobyl is a dummy variable for individuals reporting that their health has been affected by Chernobyl. Full set of controls as in Table 2, column 3, and the inter-regional migration matrix 1986–2003. Standard errors clustered at oblast level in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Source: UHBS 2004–2006; sample restricted to match the ULMS sample definitions.

respondent's health was affected by the nuclear disaster.[44] The regression results reveal that higher exposure doses significantly increase the likelihood of suffering from depression or chronic anxiety 20 years after the disaster (column 1). A one unit increase in natural background radiation raises the incidence of diagnosed mental disorders by about 1.7 percentage points in the low-dose population. The subjective measure of having been hit by Chernobyl yields similar results (column 2). Although it is re-assuring to find similar effects using two different disaster measures, the results using the second measure should be interpreted cautiously due to the potential endogeneity of the subjective measure.

Areas with more radiation were subject to more extensive medical screenings (WHO 2006). To rule out potential supply side effects of medical check-ups, we conduct a robustness check by controlling for average regional doctor contact rates. The qualitative results remain unchanged (columns 3 and 4) with one additional unit of background radiation adding about 50% to the depression incidence rate.

4.2. Possible interpretation: reduced subjective life expectancy

Can these significant long-run Chernobyl effects on subjective and objective mental health be explained by greater anxiety and uncertainty about future health status described in Section 2.2? While a direct measure on this channel does not exist, the ULMS survey provides information on subjective life expectancy in the form of subjective survival probabilities.[45] If the disaster increased respondents' worries about their future health outcomes, we expect affected persons to report lower subjective survival probabilities. And indeed, the results in Table 4 reveal that Chernobyl has significantly reduced subjective life expectancies. In the full specification (column 3), one additional unit of natural background radiation reduces the expected survival probability by 7.5 percentage points, which is equivalent to a reduction by 28% of a standard deviation.

4.3. Discussion and further implications

Our evidence unambiguously points to a large negative long-run effect of the Chernobyl disaster on subjective well-being and objective mental health. The magnitude of the disaster effect is comparable for all three outcomes: A one unit increase in natural background radiation leads to a reduction in life satisfaction and subjective survival probability by 20% and 28% of a standard deviation, respectively; it increases the incidence of depression by 21% of a standard deviation. The persistence of the effect seems to stem from the uncertainty regarding individual health consequences as suggested by significantly reduced subjective survival probabilities. Importantly, the negative Chernobyl effect is already net of physical health conditions, i.e. conditioning on the most highly discussed transmission channel. This is in line with previous evidence which finds no adverse physical health effects for the adult population (Lehmann and Wadsworth 2011). Hence, we provide the first representative and long-term evidence that the most relevant public health consequences for the low-dose population relate to mental health.

Psychologists postulate that affected individuals who suffer from psychological illnesses, depression or anxiety exhibit higher levels of lethargy and listlessness (Osiatynski 2004; Udovyk 2007). We hypothesize that such feeling of powerlessness and the perception of not being able to help oneself might cause a greater dependency on social benefits. So far, no quantitative assessment of this potential behavioral long-term implication of Chernobyl exists. This behavioral effect is estimated based on differences in social benefit dependency between more and less affected individuals. For the dependent variables we calculate the share of social transfers in total household income as reported by household heads in the ULMS (excluding any Chernobyl assistance payments) and a dummy for benefit take-up.[46] This exercise focuses on working-age adults to account for the fact that most pension-aged individuals in Ukraine rely exclusively on state benefits and that pension benefits are *de-facto* almost uniform and paid out to all elderly (Danzer 2013).[47]

In line with our conjecture, we find a significant positive effect of Chernobyl on transfer dependency: affected working-aged persons have a 3.5–4.4 percentage point higher transfer share in total income (Table 5). This result is driven by an increased benefit take-up rate rather than higher benefit levels.[48] This seems plausible since transfer allocation rules are rigid and, hence, benefit levels should not differ by disaster exposure. Nevertheless, more affected individuals seem to be more reliant on income sources provided by the state which could be consistent with mental health deterioration. Using the estimates from Table 5 we calculate the fiscal equivalents of these additional social transfers accruing to the state at 0.5–0.6% of GDP by computing $(\sum_{i=1}^{I} Y_i \times N_{WA}/N_A \times \beta_1)/GDP$, with Y_i denoting annual income of household i and N denoting number of household members who are adults (A) or of working age (WA). Higher

[44] The question in the UHBS questionnaire reads: "Has your health been affected by the Chernobyl catastrophe?"

[45] For earlier applications of subjective survival probabilities in economics see, e.g., Hamermesh (1985) and Hurd and McGarry (2002).

[46] Transfers under investigation are unemployment benefits and social assistance (incl. family allowance, child allowance, maternity benefits, single-parent allowance, low-income family benefits, disability benefits etc.). Household income includes all types of payments (including payments in the form of goods and services) and transfers that the household received in the last month (after tax).

[47] Due to the Soviet full employment policy, all elderly are eligible for a full old-age pension.

[48] The effect on benefit levels conditional on take-up is zero (results available upon request). Note, that the level of social benefits was considered very low in Ukraine during the 2000s. Many eligible persons did not claim assistance. For instance, the replacement rate of unemployment benefits in 2003 was below 26% and benefits were sometimes irregularly paid out, so that less than half of all jobless workers registered as unemployed (Kupets 2006).

Table 4
The long-run effect of Chernobyl on subjective survival probability.

	(1)	(2)	(3)
Dependent variable	*Subjective probability of survival to target age (0% to 100%)*		
Radiation	−10.391***	−7.417***	−7.500**
	(3.381)	(2.526)	(2.739)
Region and settlement FE	✓	✓	✓
Year and month FE	✓	✓	✓
Age and Gender	–	✓	✓
Remaining controls	–	–	✓
Observations	1958	1958	1958
R-squared	0.138	0.203	0.246

Notes: The target age is 65 for those aged 46 to 55, 70 for those aged 56 to 60, 75 for those aged 61 to 65, and 80 for those aged 66 to 75. The included control variables are as in Table 2. The questions on the survival probabilities were asked only to individuals aged 46 and above and only in the ULMS 2007. Standard errors clustered by radiation region as of 1986 in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$ Source: ULMS 2007.

benefit receipt in the working age population might not in itself be considered a direct economic loss as benefits are merely redistributed across population subgroups. There is, however, a deadweight loss of taxation (Gruber 2010). Assuming a deadweight loss of 0.4 per US dollar yields an aggregate welfare loss of $0.5 \times 0.4 = 0.2\%$ of Ukraine's GDP per year. This loss has been accruing for twenty years by now.

5. The monetary evaluation of the aggregate welfare loss

The identified mental and well-being effects point to a significant aggregate welfare loss in the low-dose population. This aspect of the catastrophe has received very little attention in the political and academic debate and has not been included in any cost assessment of the Chernobyl disaster to date. We fill this gap by computing the monetary value of the welfare loss.

Since catastrophes can only be evaluated *ex-post*, hedonic *ex-ante* approaches are not applicable. The most suitable methods for computing the monetary welfare loss seem to be either stated preference (explicit willingness to pay) or life satisfaction approaches (which allow calculating an implicit willingness to pay; see, e.g., Levinson 2012 or Lüchinger 2009). In the context of nuclear power, the former method has been applied for the *ex-ante* willingness to accept compensation in exchange for the location of a nearby underground nuclear waste repository in Nevada, USA. Kunreuther and Easterling (1990) conducted a telephone survey offering randomized compensation packages to local residents but found that the compensation was most often deemed inappropriate because of security worries. Taking into account additional concerns about strategic responses and framing effects which are inherent to this method (Levinson 2012) we follow the life satisfaction approach. The goal of this approach is to *ex-post* estimate the amount of monetary compensation required to close the relative mental well-being gap of affected persons (Clark and Oswald 2002; Levinson 2012). In this framework Eq. (1) represents a utility or utilitaristic welfare function in which life satisfaction is assumed to proxy for experienced utility. Thus, the coefficient of radiation expresses the marginal disutility from the disaster. Using the marginal rate of substitution between radiation and income (the relative size of the radiation to the income coefficient), we compute the monetary compensating differential required to make affected and unaffected individuals equally well-off.[49]

Table 5
The long-run effect of Chernobyl on the transfer dependency of working-age adults.

	(1)	(2)	(3)	Mean
Dependent variable	*Transfer share in income (%)*			*0.086*
Radiation	0.044***	0.036**	0.035**	
	(0.014)	(0.016)	(0.014)	
R-squared	0.095	0.140	0.226	
Dependent variable	*Benefit take-up (binary variable)*			*0.106*
Radiation	0.039**	0.039**	0.029*	
	(0.019)	(0.020)	(0.016)	
R-squared	0.067	0.104	0.146	
Region and settlement FE	✓	✓	✓	
Year and month FE	✓	✓	✓	
Age and Gender	–	✓	✓	
Remaining controls	–	–	✓	
Observations	7985	7985	7985	

Notes. OLS models. The included control variables are as in Table 2 plus dummies for the number of working and the number of pension-receiving household members. Working age is up to age 55 (60) for women (men). Robust standard errors clustered by radiation region in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Source: ULMS 2003–2007; own calculations.

We perform the analysis for two scenarios: In the first one, every affected Ukrainian citizen is compensated according to the estimated average radiation and income effects. The second scenario uses a radiation threshold z of 0.8 mSv above which citizens are compensated with a unitary benefit while persons below the threshold remain uncompensated. To attain the relevant coefficients for the threshold model we estimate semi-log Eq. (2) in which $\hat{\beta}_{inc}$ gives the change in the dependent variable y (utility) due to a one log point change in uncompensated total monthly household income[50] (expressed in June 2004 values), while the utility loss due to radiation above threshold z (indicated by a dummy variable) is given by $\hat{\beta}_{rad,z}$[51]:

$$y_{ikt} = \beta_0 + \beta_{rad,z} RadiationDummy_{j86,z} + \beta_{inc} \log(income_{it}) + X'\gamma + \tau_k + \sigma_t + \theta_m + \varepsilon_{ikt}. \quad (2)$$

We then aggregate and express the relative income change required for neutralizing the negative disaster effect as a fraction of annual GDP:

$$\left[\left(\exp\left(\frac{-\hat{\beta}_{rad}}{\hat{\beta}_{inc}}\right)-1\right) \times \overline{Y}^{uncomp}_{household} \times 12 \times \frac{N}{household\ \ size}\right] \Big/ GDP, \quad (3)$$

with $\overline{Y}^{uncomp}_{household}$ being the average uncompensated monthly household income and N being the size of the compensated population.

A usual concern with the life satisfaction approach is that the income variable might suffer from endogeneity and measurement error. If this resulted in a downward bias of the estimated income coefficient, the calculated compensation for the welfare loss would be artificially inflated. We address these potential problems in two ways. First, we instrument household income by a Bartik (1991) style income predictor based on the detailed retrospective wage data for the year 1986 from ULMS. We capitalize on pre-existing cross-sectional variation in wages across industries in the Soviet Union and the distribution of industries across regions. Average wages of industries which are typical for a specific area (27 oblasts × 3 settlement types city/town/village) are multiplied with the national industry wage growth from 1986 to 2003 in order to predict the expected wage/income level based on the historical 1986 industry structure (differentiating between 11 industries).[52] The resulting Bartik instrument is a very strong predictor for actual household incomes (see Fig. A-2). Additionally, we show results using a novel instrument for income in a life satisfaction regression proposed by Danzer and Danzer (2015). The instrument exploits quasi-experimental variation in income caused by unexpected and substantial increases in Ukraine's legal minimum pension benefits in the year 2004

[49] This approach does not come without strong assumptions. However, as discussed and highlighted by Levinson (2012), these are no stronger than the assumptions underlying alternative methods.

[50] There are several advantages to using household instead of individual income: households tend to pool resources and also have joint expenditures and the measure of household income provides a more complete assessment of non-wage income sources.

[51] The base category comprises individuals with additional radiation below 0.2 mSv.

[52] The instrument for each region is calculated as national average excluding the oblast of interest.

Table 6
The effect of income on life satisfaction based on OLS and 2SLS regressions.

Estimation Sample	(1) OLS Full sample	(2) 2SLS Full sample	(3) OLS ±6 years around pension age	(4) 2SLS ±6 years around pension age
Dependent variable	Life satisfaction			
Radiation	−0.196***	−0.175**	−0.122**	−0.120**
	(0.052)	(0.070)	(0.052)	(0.054)
Log income	0.152***	0.320***	0.211***	0.391***
	(0.016)	(0.066)	(0.031)	(0.114)
Full set of controls	✓	✓	✓	✓
Observations	11,922	11,922	3217	3217
R-squared	0.200	0.161	0.179	0.163
Instrument		Bartik sector income instrument		Pension eligibility × reform date
F statistic (first stage)		162.2		69.4

Notes: Dependent variable is standardized with mean of zero and std. of one. All four regressions contain the full set of controls as in Table 2, column 3. The F Statistics of the first stages are reported at the bottom the table. Robust standard errors clustered by region of radiation in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1. Source: ULMS 2003–2007; own calculations. The regressions in columns 3 and 4 are based on the subsample of persons around the official pension age.

(for details on the reform and Ukraine's pension system, see Danzer 2013). The causal effect of income on life satisfaction is identified in a difference-in-differences framework comparing pension-eligible versus not-yet eligible elderly over time. Importantly, old-age pension eligibility and receipt only depend on age and not on actual work or retirement status. Old-age pensions are de-facto flat benefits. The downside of this instrument is its narrow scope as the income effect can only be estimated for individuals close to the official pension age (± six years around official pension age which is 55 for women and 60 for men). The corresponding OLS and IV results are summarized in Table 6. For both instrumental variables, the 2SLS estimates are about twice as large as the conventional estimates suggesting that the original income coefficients are biased. The doubling of the coefficients is in line with the previous literature which found two to three times larger IV than OLS estimates (Luttmer 2005; Lüchinger 2009; Levinson 2012).

Calculating the monetary compensation necessary to off-set the welfare loss yields the following results: Using the first instrument, compensation equals 31–75% of average monthly household income, or 26–61 real 2004 USD per household and month (Table 7, Panel A).[53] Clearly, compensating only the most affected individuals raises the monthly amount per household but reduces the population base receiving benefits. The aggregate welfare loss adds up to additional 4.2–5.5% of Ukrainian GDP per year. This implies that the uncompensated implicit costs are almost in the order of magnitude of the explicit current disaster relief and liquidation spending of Ukraine (5–7% of GDP per year; Oughton et al. 2009). The calculations using the second instrument provide a lower bound benchmark (Table 7, Panel B); recall that the Chernobyl effect among the elderly is smaller than for the entire sample while the income coefficient is larger (Table 2). Basing our welfare calculations for the entire sample on these conservative values yields a lower, but still substantial annual welfare loss of 2.2–2.4% of GDP.

6. The value of a statistical life year

The life satisfaction approach can also be used to evaluate the value of a statistical life year (VSLY). VSLY estimates are widely used in public policy to assess the cost associated with environmental hazards or with medical interventions (Ashenfelter 2010). While typical VSLY approaches rely on objective life risks which have been deliberately chosen by individuals (through occupational choices or risky behavior), the risks stemming from Chernobyl are exogenous; further, our approach is non-standard as the changes in life expectancies are perceived rather than real. Nevertheless it allows us to produce VSLY estimates which can be compared to prior research.

[53] In comparison, the compensating differential for suffering from a chronic physical disease is 36 USD.

How much additional income would be required to compensate individuals for their perceived loss in lifetime? In order to estimate the VSLY differential for Chernobyl affected individuals we need information about the number of perceived lost life years θ and an estimate of how much individuals would be willing to pay in order to live up to normal (unaffected) age. These two numbers can then be used to compute the VSLY according to the following formula:

$$VSLY = \sum_{t=1}^{s} \frac{1}{(1+\sigma)^t} \left[\left(exp\left(\frac{-\hat{\beta}_{lostlife}}{\hat{\beta}_{inc}} \right) - 1 \right) \times \overline{Y}_{annual}^{uncomp} \right] \times \frac{1}{\theta} \tag{4}$$

Where s is the life expectancy, t is year, σ is the discount rate, $\hat{\beta}_{lostlife}$ is the estimate of the effect of number of perceived lost years on life satisfaction and $\hat{\beta}_{inc}$ is the income coefficient on the uncompensated, annual income using the Bartik instrument. The underlying IV regressions are similar to Eq. (2) but use a measure for number of perceived lost life years rather than a radiation indicator. The procedure to compute the number of perceived lost life years is described in Appendix D. The regressions control for employment and health status to eliminate individual risks pertaining to these domains.

Our empirical VSLY estimate ranges between 23,000 and 33,000 USD (as of 2004; Table 8).[54] These values are at the lower end of the estimate range for industrialized countries between 20,000 and 130,000 USD (Viscusi and Aldy 2003; data in year 2000 USD) and are between half and two third of the typical 50,000 USD VSLY assumed in insurance markets of industrialized countries (Ashenfelter 2010). The life-time VSL derived from our estimates ranges between 1.7 and 2.5 m USD which is much higher than previously reported numbers for Ukraine; Kaneva and Kartashova (2014), for instance, estimate the value of a statistical life from occupational risks at only 125–190,000 USD—which seems unrealistically low. Our estimate is comparable to the 2.4 m USD VSL estimated for Poland by Giergiczny (2008).

7. Conclusions

This paper sheds slight on the hidden and previously unquantified welfare loss from the largest nuclear accident on record. We analyze the effects of the Chernobyl disaster on mental well-being of the low-dose population in Ukraine 20 years after the accident; we exclude individuals who were exposed to high doses of radiation. To identify the causal effect of Chernobyl we assign regional radiation doses to

[54] We also perform sensitivity analyses: Higher discount rates obviously imply lower VSLY values; however, they also narrow the range between VSLY estimates for different age groups. While the range of estimates is 21,000–28,000 USD for $\sigma = 3\%$, it is only 19,000–23,000 USD for $\sigma = 4\%$. We also compute VSLY with age adjustment; qualitatively, the values remain in the same range.

Table 7
Compensating differentials and share of total compensation in GDP.

		$\hat{\beta}_{rad}$ (in units of background radiation)	$\hat{\beta}_{inc}$	$exp(\frac{-\hat{\beta}_{rad}}{\hat{\beta}_{inc}})$	Compensated population (million)	Monthly household compensating differential (in USD)	Share of annual GDP
Panel A. Instrumental variable I (Bartik sector income instrument)							
I.	Compensation w/o threshold	−0.175	0.320	1.31	38.1	25.5	4.2%
II.	High radiation threshold	−0.134	0.239	1.75	20.8	61.0	5.5%
Panel B. Instrumental variable II (Pension eligibility × reform date)							
III.	Compensation w/o threshold	−0.120	0.391	1.17	38.1	13.5	2.2%
IV.	High radiation threshold	−0.111	0.389	1.33	20.8	147.9	2.4%

Notes: The coefficients for computing Eq. (3) are measured in mSv [$\hat{\beta}_{rad}/2$]. The high radiation threshold is 0.8 mSv. All reported coefficients are significantly different from zero. $\overline{Y}^{uncomp}_{household} =$ 446.4. Exchange rate: 1 UAH = 0.18192 USD. Average household size: 3.4.

individuals according to their place of residence at the time of the catastrophe. The results suggest that affected individuals exhibit significantly lower levels of mental well-being as demonstrated by reduced life satisfaction and increased incidence rates of depression and chronic anxiety. We provide suggestive evidence that worries about future health outcomes are one significant transmission channel through which the catastrophe impacted mental well-being: Affected individuals report significantly lower subjective survival probabilities which points to a reduced perceived life expectancy. As a behavioral consequence, we find that more affected individuals rely to a greater extent on governmental social benefits as a source of livelihood, accruing to 0.5% of GDP per year. Taking our results one step further, we estimate the aggregate annual compensating differential needed to offset the long-run welfare loss of the low-dose population at 2.2–5.5% of Ukraine's GDP as of 2004. This suggests that the overall costs to society caused by the Chernobyl catastrophe significantly exceed the actual recovery and compensation costs of around 5–7% of GDP per year. Since our results are based on the 96% of the Ukrainian population that has received very low radiation doses, the well-being effects and welfare costs for the entire population (including the highly affected) will be even higher.

This paper has suggested that governmental countermeasures against the disaster provided signals for disaster exposure which in turn prompted mental distress. Yet, we caution the reader not to conclude prematurely that these countermeasures were taken irresponsibly. Not only is the counterfactual without governmental countermeasures unknown; in fact, politicians had to respond very quickly in 1986 without today's available knowledge about realized consequences. However, the information policy of governments in the aftermath of such accidents is an extremely difficult challenge and responsible actors have tended to downplay the true risks—thus endangering a loss in credibility; this also holds for advanced democracies. The literature on risk communication suggests that more credible information about

Table 8
Estimates for Values of Statistical Life Years (VSLY) after Chernobyl.

Age group	Approx. remaining life expectancy	Lost life years	Annual compensation per remaining life year (2004 USD)	Cost of one year of statistical life (2004 USD)
45–49	29	2.80	5687.74	33,172
50–54	25	2.65	5687.74	32,706
55–59	21	2.45	5687.74	32,165
60–64	18	2.25	5687.74	31,859
65–69	14	2.20	5687.74	27,431
70–75	9	1.90	5687.74	22,544

Note: Approximate remaining life expectancy is computed based on Góra (2008). Lost life years are computed using a Weibull survivor function $S(t) = exp(-\lambda t^{\alpha})$ with $\lambda = 0.001$; $\alpha = 2.9/2.85$ for the samples below and above median radiation. Annual compensation per remaining life year is computed from $(exp(\frac{-\hat{\beta}_{lostlife}}{\hat{\beta}_{inc}}) - 1) \times \overline{Y}^{uncomp}_{annual}$. The cost of one year of statistical life is the net present value of real annual compensation payments over the remaining life expectancy with discount rate $\sigma = 2\%$.

the potential impact of the disaster might have reduced the negative mental toll taken by the catastrophe (Rubin et al. 2012). In general, post-disaster psychological morbidity can be further reduced by adequate mental health interventions and sufficient provision of mental health care services (Bromet et al. 2011).

The world has seen 25 nuclear accidents in the past 60 years and many more technical disasters (Sovacool 2008) suggesting that the largest nuclear catastrophe provides lessons beyond Ukraine. As the catastrophes in the Fukushima Daiichi (Japan, 2011) and Three Mile Island (USA, 1979) nuclear power plants have clearly shown, such accidents can happen everywhere, even in the richest countries with the highest safety and security standards; and people there, too, seem to react with elevated levels of mental distress (for short-term evidence, see Norris et al. 2002a, 2002b; Bromet 2012; Shigemura et al. 2012). Our study provides unique policy relevant evidence about a previously neglected welfare consequence of nuclear accidents—an important aspect which probably applies to technological disasters in general. This can inform governments which ultimately have to bear the costs of nuclear and other large-scale accidents due to the lack or limitation of private insurance (Faure and Skogh 1992; Laes et al. 2011). History has shown that the costs caused by nuclear accidents have to be borne by the taxpayer no matter whether nuclear power is produced by private or state owned companies. Cost–benefit analyses of energy technologies should recognize these individual and aggregate well-being and welfare consequences of high-cost, low-frequency disasters.

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Appendix A. Supplementary data

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