Environmental Modelling & Software 79 (2016) 343–353

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Modeling human genetic radiation risks around nuclear facilities in Germany and five neighboring countries: A sex ratio study

Hagen Scherb [a,*], Ralf Kusmierz [a], Magdalena Sigler [a], Kristina Voigt [a]

[a] Helmholtz Zentrum München – German Research Center for Environmental Health, Institute of Computational Biology, Ingolstädter Landstr. 1, D-85764 Neuherberg, Germany

ARTICLE INFO

Article history:
Received 2 June 2015
Received in revised form
21 October 2015
Accepted 22 October 2015
Available online 4 November 2015

Keywords:
Big data
Change-point
Environmental health risk modeling
Nuclear facilities
Radiation induced genetic effects
Rayleigh function
Sex odds
Shifted Gaussian function
Variogram analysis

ABSTRACT

Ionizing radiation causes genetic mutations, and nuclear facilities, research reactors, and power reactors discharge radionuclides and neutrons. On the basis of exhaustive municipality data, we considered the human birth sex ratio in 78 million births in Austria, France, Germany, Luxembourg, Switzerland, and The Netherlands (1957–2013). We present a novel environmental health modeling concept expressing the spatiotemporal association of the sex ratio with minimum distance from operating or decommissioned nuclear facilities. Spatial correlation of the sex ratio is assessed by directional and omnidirectional semivariogram analyses. We detected elevated human sex ratios near nuclear facilities, whether we analyzed comprehensive groups of nuclear installations, or looked at individual facilities in a descriptive and exploratory manner. The sex ratio increases are typically between a few per mill and a few percent, and they occur in regions of up to 40 km around the nuclear installations. Intensifying research in the field of radiation induced genetic effects is recommended.

1. Introduction

Energy use is central to human societies and provides many health benefits. However, each source of energy entails some environmental and health risks (Smith et al., 2013). Ionizing radiation generated during nuclear energy production has impacts on the environment and on human beings. It has been known for almost one century that ionizing radiation at low doses (<100 mSv) causes genetic mutations (Muller, 1927). It was Muller's hypothesis that even background radiation (approximately 1 mSv) entails harm according to the "linear no threshold theory (LNT)". The environment as well as mankind is not only exposed to natural background ionizing radiation but also to man-made radioactive elements from multiple sources. Incomplete knowledge in the radiation sciences has recently been codified again by the order of the US "Low-Dose Radiation Research Act of 2015" (https://www.govtrack.us/congress/bills/114/hr35/text). Table 1 lists pertinent literature with positive findings on radiation induced genetic effects: congenital malformations, perinatal mortality including stillbirths, birth sex ratio, and childhood cancer.

Radioactive releases from nuclear facilities may cause genetic effects, e.g., leukemia in surrounding populations, and the sex ratio and stillbirths increased after nuclear accidents (Gardner, 1991; Grech, 2014a; Scherb et al., 1999; Sermage-Faure et al., 2012; Spix et al., 2008). Concerns about increased environmental risks near nuclear power plants during fuel element exchange have been raised by Ghirga (2012). In April 2010 the U.S. Nuclear Regulatory Commission (NRC) asked the National Academy of Sciences (NAS) to analyze "radiogenic cancer mortality and total cancer mortality in populations living near past, present, and possible future commercial nuclear facilities for all age groups," and to conduct corresponding analyses for cancer incidence. Before beginning the full study in late 2011, the NAS was required to conduct a scoping study to determine the best study design for assessing those risks (Wing et al., 2011).

An important indicator in the context of radiation induced sex-linked lethal mutations in man is the sex ratio in humans at birth; technically sex odds: male/female (Grech, 2014a, b; Schull and Neel,

* Corresponding author.
E-mail addresses: scherb@helmholtz-muenchen.de (H. Scherb), ralf.kusmierz@helmholtz-muenchen.de (R. Kusmierz), kvoigt@helmholtz-muenchen.de (K. Voigt).

http://dx.doi.org/10.1016/j.envsoft.2015.10.019
1364-8152/

Table 1
Literature on radiation induced genetic effects: increases in congenital malformations, stillbirths, perinatal mortality, birth sex ratios, and childhood cancers.

Effect by exposure	Reference
Birth defects	
Congenital malformations in radiology	(Macht and Lawrence, 1955)
Neural tube defects at Hanford, USA	(Sever et al., 1988)
Birth defects after Chernobyl (April 1986)	(Lazjuk et al., 2003)
Down syndrome after Chernobyl	(Laziuk et al., 2002)
	(Zatsepin et al., 2007)
	(Metneki and Czeizel, 2005)
	(Sperling et al., 1991; Sperling et al., 2012)
Cleft lip and palate after Chernobyl	(Zieglowski and Hemprich, 1999)
	(Scherb and Weigelt, 2004)
General birth defects after Chernobyl	(Wertelecki, 2010)
	(Scherb and Weigelt, 2003)
Stillbirths and perinatal mortality	
Father's occupational exposure	(Parker et al., 1999)
Chernobyl	(Auvinen et al., 2001)
	(Körblein and Küchenhoff, 1997)
	(Scherb et al., 2000; Scherb et al., 1999)
Birth sex ratio	
Mother's therapeutic exposure	(Scholte and Sobels, 1964)
Father's occupational exposure	(Dickinson et al., 1996)
Atomic bomb testing	(Grech, 2015; Scherb, 2015)
Windscale/Sellafield (October 1957)	(Scherb and Voigt, 2007, 2011)
Chernobyl	(Scherb et al., 2013b, 2014a, b)
Background radiation Kerala/India	(Grech, 2014a, b; 2015)
	(Koya et al., 2015)
Childhood cancer	
Nuclear power plants in Germany	(Spix et al., 2008)
Nuclear power plants in France	(Sermage-Faure et al., 2012)
CT scans in the United Kingdom	(Pearce et al., 2012)
CT scans in Australia	(Mathews et al., 2013)
Background radiation in Switzerland	(Spycher et al., 2015)

1958). However, relatively little research has been carried out in this field since the 1960s despite extensive nuclear weapons testing and increasing production of nuclear power. At least the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has acknowledged as early as in 1958 that an increase in the frequency of dominant mutations in humans associated with visible effects would manifest itself to some unknown extent as an increase in the frequency of malformations and stillbirths as well as in sex ratio shifts (http://www.unscear.org/unscear/en/publications/1958.html). Consideration of the odds of male to female offspring at birth may therefore be a simple and non-invasive way to monitor the reproductive or genetic health of a human population (Scholte and Sobels, 1964). Except in societies where selective abortion skews the sex ratio (SR), approximately 105 boys are born for every 100 girls. Ein-Mor et al. (2010) concluded from a large retrospective cohort study that the sex ratio at birth is remarkably constant. Terrell et al. (2011) examined whether environmental or occupational hazards alter the sex ratio at birth. Factors evaluated in the review by Terrell et al. included ionizing radiation as well as chemicals (Scherb and Voigt, 2007; Voigt et al., 2012).

In many studies on the influence of ionizing radiation on the human secondary sex odds, an increase (not necessarily significant) was detected (Koya et al., 2015; Mudie et al., 2007). James (1997) even postulated that radiation is the only known reproductive hazard that increases the sex ratio. Scherb and Voigt reported increases in the human sex odds at birth in Europe and Cuba after the Chernobyl Nuclear Power Plant accident (Scherb et al., 2013b; Scherb and Voigt, 2011). Grech (2014a) published a birth ratio study for Scandinavia and the United Kingdom after the nuclear accident at Windscale, October 1957. He found a significant rise in the sex ratio for Norway and Sweden, not for the United Kingdom. Generalizing Grech's approach, we were able to show that after Windscale the sex odds jumped significantly in exposed downwind countries but remained undisturbed in less affected upwind countries (Scherb et al., 2014b). Grech also reported substantial sex odds increases in the former European and Asian Soviet Republics after Chernobyl and, globally, after the atmospheric atomic bomb testing (Grech, 2015; Scherb, 2015). Moreover, previous work provides considerable evidence that not only after nuclear accidents but also near normally running nuclear power plants and especially in the vicinity of nuclear processing and storage sites, the human sex ratio at birth is distorted and in some places to a rather large extent so (Scherb and Voigt, 2011, 2012a, b; Scherb et al., 2014c).

Bennett et al. (2013) reviewed numerical, graphical, and qualitative methods and metrics for characterizing performance of environmental models and elaborated that the selection of methods must be tailored to the model scope, quality of data, and information available. In this spirit and introducing the additional basic however meaningful metric “sex ratio”, the purpose of this paper is the paradigmatic development and the propagation of a novel environmental modeling concept and the recommendation and exemplarily application of corresponding computational and statistical tools for the evaluation of spatiotemporal trends in the human sex odds at birth exemplified around 67 major nuclear facilities in six European countries (Fig. 1) on the basis of exhaustive annual municipality data (Table 2). Within the “Thematic Issue on Modeling Human and Ecological Health Risks”, the devised method covers the topic “Methodological developments in the assessment of radiation and chemicals' risks” utilizing most recent and high-performance statistical software. Our concept can also be applied to other spatiotemporally structured risk factors and corresponding population health metrics like, e.g., chemical exposure, disease incidence, and mortality statistics. Last but not least, our approach may encourage citizen science since all data used and analyzed here are aggregated official data, which are freely available to everyone.