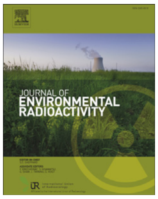
Journal of Environmental Radioactivity 164 (2016) 354–364

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

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



Quantile regression and Bayesian cluster detection to identify radon prone areas

Annalina Sarra [a, *], Lara Fontanella [b], Pasquale Valentini [a], Sergio Palermi [c]

[a] *Department of Economics, Viale Pindaro, 42 -65127 Pescara, G. d'Annunzio University, Italy*
[b] *Department of Legal and Social Sciences, Viale Pindaro, 42 -65127 Pescara, G. d'Annunzio University, Italy*
[c] *Agency of Environmental Protection of Abruzzo (ARTA), V.le G. Marconi, 178, 65127 Pescara, Italy*

ARTICLE INFO

Article history:
Received 22 February 2016
Received in revised form
14 June 2016
Accepted 18 June 2016

Keywords:
Radon
Building factors
Bayesian spatial quantile regression
Standard house
Bayesian cluster detection

ABSTRACT

Albeit the dominant source of radon in indoor environments is the geology of the territory, many studies have demonstrated that indoor radon concentrations also depend on dwelling-specific characteristics. Following a stepwise analysis, in this study we propose a combined approach to delineate radon prone areas. We first investigate the impact of various building covariates on indoor radon concentrations. To achieve a more complete picture of this association, we exploit the flexible formulation of a Bayesian spatial quantile regression, which is also equipped with parameters that controls the spatial dependence across data. The quantitative knowledge of the influence of each significant building-specific factor on the measured radon levels is employed to predict the radon concentrations that would have been found if the sampled buildings had possessed standard characteristics. Those normalised radon measures should reflect the geogenic radon potential of the underlying ground, which is a quantity directly related to the geological environment. The second stage of the analysis is aimed at identifying radon prone areas, and to this end, we adopt a Bayesian model for spatial cluster detection using as reference unit the building with standard characteristics. The case study is based on a data set of more than 2000 indoor radon measures, available for the Abruzzo region (Central Italy) and collected by the Agency of Environmental Protection of Abruzzo, during several indoor radon monitoring surveys.

1. Introduction

Threat posed to health by radon is generating a growing attention by national and international authorities aimed at assessing the exposure of people to this radioactive gas and identifying those geographical areas where high indoor radon concentrations are more likely to be found. Those high risk zones are often referred to as "radon-prone areas". Over the last decades, national radon surveys have been carried out in many western countries, e.g. in the U.S. (USEPA, 1992; White et al., 1992), U.K. (Green et al., 2002), Ireland (Fennell et al., 2002), Finland (Weltner et al., 2002), Germany (Kemski et al., 1996), Austria (Friedmann, 2005) and Italy (Bochicchio et al., 1996). Those surveys represent a fundamental step of national radon programmes, in order to get the necessary awareness for evaluating the range of the radon concentration problem, interpreting monitored data and formulating adequate future actions designed to reduce the hazards arising from the exposure to radon. A large number of studies have documented that the dominant source of radon in indoor environments is the radon in the soil gas, whose concentration is linked to the geological features of the territory. More precisely, indoor radon is influenced by the permeability of the soil and the underlying rock, and by the radium and moisture content of the soil (Apte et al., 1999; Ielsch et al., 2010; Miles and Appleton, 2005; Sundal et al., 2004; Zhu et al., 2001). There have been also several efforts to account for the multifactorial dependence of indoor radon concentrations via models which combine different explanatory variables, such as housing characteristics, soil properties, geology and radiometric factors (see, for example, Levésque et al., 1997; Price et al., 1996; Apte et al., 1999; Smith and Field, 2007; Smethurst et al., 2008; Kemski et al., 2009; Appleton et al., 2011; Nissi et al., 2012; Pasculli et al., 2014; Kropat et al., 2015). The majority of these works have the purpose of evaluating the impact of given variables on the average indoor radon concentrations. However, the employment of traditional regression analysis, based on measures

---

[*] Corresponding author. Department of Economics, Viale Pindaro, 42 -65127 Pescara, G. d'Annunzio University, Italy.

E-mail address: asarra@dmqte.unich.it (A. Sarra).

http://dx.doi.org/10.1016/j.jenvrad.2016.06.014
0265-931X/

of central tendency, typically the mean, may be inefficient when the intrinsic interest is on the tails of distributions. In addition, when data are characterised by spatial heterogeneity, outliers and asymmetry, and if reference concentration values endorsed by law or international recommendations[1] have to be taken into account, the conditional mean models are not well equipped to summarise the behaviour of the response variable for fixed values of the predictors. A more robust approach, able to provide a better understanding of how radon concentrations are affected by the selected predictors, is offered by the quantile regression technique (see, for an introduction, the seminal work of Koenker and Bassett, 1978). Technically, this method extends the notion of conditional mean modelling to a quantile framework, allowing to study the change in one or several portions of a response variables' distribution. Although quantile regression is gaining popularity in literature, attracting a lot of interest, with useful applications in various fields, such as medicine (Cole and Green, 1992; Heagerty and Pepe, 1999), economics (Hendricks and Koenker, 1992; Buchinsky, 1995), ecology (Cade and Noon, 2003; Cade et al., 2005) and hydrology (Pandey and Nguyen, 1999) (Pandey and Nguyen, 1999), little research exists in the radon mapping context. Some exceptions are represented by the works of Borgoni (2011) and Fontanella et al. (2015). Both the above mentioned papers define a conditional quantile regression that incorporates spatial dependence. Distinctively, in the first paper the structure of the quantile regression function, specified to account for the effects of various potential influential factors on indoor radon concentrations, is enriched by defining a spatial autoregressive model. Conversely, Fontanella et al. (2015) perform a spatial quantile regression analysis through a hierarchical Bayesian model, in which the matrix of the explanatory variables is partially defined by a set of spatial common latent factors and the spatial structure is incorporated into the model error term by specifying a spatial asymmetric Laplace process, as suggested by Lum and Gelfand (2012). Following those lines of research, the aim of this paper is twofold. We first investigate the impact of various building covariates on indoor radon concentrations. In this respect, we specify a Bayesian spatial quantile regression model, which is also equipped with parameters that control the spatial dependence across data. This flexible model permits to delineate different building profiles, according to their proneness to high radon concentrations. We exploit the quantitative knowledge of the influence of each significant house-specific factor on the measured radon level, to predict the radon concentration that would have been found if that building had possessed standard characteristics, which is a quantity directly related to the geological environment (i.e. geogenic radon potential of the underlying ground) (Gruber et al., 2013; Tung et al., 2013). The geogenic radon potential concept has been widely used to assess radon prone areas (see, among others, Gundersen and Schumann, 1996; Kemski et al., 2001; Appleton et al., 2008, 2011; Bossew et al., 2008; Bossew, 2015; Ielsch et al., 2010; Ciotoli et al., 2016; Friedmann et al., 2016). In a second stage, we employ the house with standard characteristics as the reference unit in a Bayesian model for spatial cluster detection (Wakefield and Kim, 2013). This procedure, borrowed from the epidemiological field, aims to identify areas where the concentration of events (indoor radon levels exceeding a threshold value) is abnormally high. Results coming from this study can be of assistance to the authorities for radon risk management. In fact the adopted approach provides information valuable both in delineating guidelines for new buildings and in identifying which types of dwellings should be monitored more carefully. Besides, the spatial cluster, identified through the Bayesian cluster detection technique, can give insights on areas deserving greater attention for mitigation and research purposes. Data employed in this two-stage analysis, cover the entire area of the Abruzzo region (Central Italy) and have been collected by the Agency of Environmental Protection of Abruzzo, during several radon monitoring surveys. The rest of the paper is organised as follows. In section 2 we first describe the study area and introduce the radon data set. Next, we define the basic Bayesian spatial quantile regression model framework and give details of Bayesian inference. Finally, we focus on the Bayesian procedure for cluster detection. The case study is detailed in Section 3, in which we summarise the main results. We conclude by discussing the overlooked opportunities that spatial quantile regression, coupled with Bayesian cluster detection models, offer to radioprotection authorities.

2. Materials and methods

2.1. Study area

Abruzzo is a region located in the central part of the Italian peninsula and covers 10,795 km^2, with a population of around 1,330,000. It is divided into four administrative units (districts): L'Aquila, Teramo, Pescara and Chieti (Fig. 1(a)) and include 305 municipalities. The physiographic setting of this region (Fig. 1(b)) is defined by three main orographic and morphostructural domains: Apennine Chain, Piedmont, and Coastal Plain (D'Alessandro et al., 2003).

The relief of the Apennine Chain is made up of carbonate ridges (whose altitude can reach about 2900 m in Gran Sasso and Maiella massifs) separated by parallel valleys carved in terrigenous foredeep deposits and by wide intermontane tectonic basins partially filled with Quaternary continental deposits. On the eastern edge, the relief abruptly slopes down into the Piedmont area, where a hilly landscape is carved by cataclinal valleys in a gently NE-dipping homocline of Plio-Pleistocene sea deposits (clay, sands, conglomerates). Along the valleys and close to the coast, alluvial plains, with fluvial and alluvial fan deposits, join a narrow Coastal Plain, facing the Adriatic Sea. At a first glance, the lithologic characteristics of the regional territory (limestone, marls and sandstone in the Apennine Chain, while clay, sands and conglomerates characterise the piedmont and coastal areas) do not seem to indicate a relevant geogenic radon potential. Nevertheless, the remarkable development of fracturing (mainly related to tectonic faults) and of karst phenomena in the Apennines area (ISPRA, 2012) may produce local enhancement of radon concentration in the soil gas and, consequently, in indoor environments. In the geogenic radon potential perspective, it is also to be considered the role of circulating fluids in thermal areas and the possible occurrence of local enrichments of uranium/radium in the soil of some areas, such as those in the western edge of the L'Aquila district, close to the volcanic province of Latium.

2.2. Indoor radon measures and building characteristics

The Regional Agency for Environment Protection (ARTA) has been carrying out various indoor radon surveys in Abruzzo since early nineties. The monitoring activity of ARTA has resulted in a geo-referenced database of annual average radon concentrations measured in almost 2400 buildings, mainly homes, mostly at ground level. Further details about the surveys can be found in Palermi and Pasculli (2008) and Palermi et al. (2012). Data have been gathered in a very wide time-span (from early '90s till 2013).

---

[1] Member states of the European Union, for example, have to establish a national reference level for annual average indoor radon concentration not exceeding the value of 300 Bq/m^3 fixed by the Council Directive 2013/59/Euratom.