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Economic growth and scientific knowledge as determinants of innovation uptake in a situation of uncertainty about environmental or health risk

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Abstract

With growing concern for potential negative impacts to health or the environment of new types of consumer goods reaching the market, a major challenge for both policy makers and producers is to understand conditions of uptake of innovation in a situation of uncertainty concerning risk related to these products. Our contribution studies the effects of economic growth and of the production of new scientific knowledge on risk, on innovation uptake. It focuses on the case of polycarbonate, an intermediate good that requires the use of bisphenol A (BPA), a suspected endocrine disruptor. Polycarbonate is a widely used material found in automotive but also in baby-bottles and other plastics. Using Japanese time-series data, the autoregressive distributed lag approach is applied to estimate the relationship between aggregate material use, economic growth and new scientific knowledge about risk related to this material. Polycarbonate sales are used as a dependent variable. First, the hypothesis of an Environmental Kuznets Curve (EKC) is tested. Then, the quarterly quantity of the global number of scientific articles dealing with potential risk of BPA is included in the model.

Results support the EKC theory in so far as the model presents an inverted-U-shaped link between economic growth and polycarbonate use. There is also an inverted-U-shape curve of the relationship between the number of scientific publications and polycarbonate sales. In other words, the paper also shows that, in a first phase, the production of scientific knowledge about risk related to bisphenol A may have no negative impact on innovation uptake.

Keywords: Environmental Kuznets Curve; health; innovation; risk; scientific uncertainty; endocrine disruptor

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Abstract

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JEL classification:

JEL: D81 - Criteria for Decision-Making under Risk and Uncertainty

JEL: I18 - Government Policy; Regulation; Public health

JEL: O33 - Technological Change: Choices and Consequences; Diffusion Processes

JEL: Q55 - Technological Innovation

1. Introduction

Major areas of innovation are generally associated with potentially huge societal benefits, but the uncertainty surrounding their potential health and/or environmental impacts leads to question their net benefit to society and may jeopardize their future adoption by markets. This situation concerns 'future' innovations, i.e. those that have not yet reached the market, but also consumer goods that were considered as greatly beneficial until they became associated with risk to health or the environment.

The emergence of the problem of potentially endocrine disrupting chemical compounds is one illustration: these may be found for example in cosmetics with certain preservatives such as paraben (Sasseville et al. 2015), in the food industry with pesticides such as glyphosate (Gasnier et al. 2009), or in everyday objects containing certain plasticizers such as phthalates (Grindler et al. 2015).

Regarding risk to health or the environment for which the scientific truth is not established with certainty, public policies may be governed by the precautionary principle. This principle is for instance detailed in Article 191 of the Treaty on the Functioning of the European Union[1] and has constitutional value in several countries such as Brazil or France. The precautionary principle states that "Where the occurrence of damage, although uncertain according to the state of scientific knowledge, could seriously and irreversibly affect the environment, public authorities shall ensure by applying the precautionary principle the implementation of risk assessment procedures and the adoption of provisional and proportionate measures to prevent the occurrence of the damage[2]". One of the variables of the proportionality of the measures is the consistency of the scientific record in support of a risk hypothesis (Godard 1997). A prohibition cannot therefore be based on an unfounded scientific assessment, and at the same time a precautionary measure may consist precisely in developing scientific research to better characterize a risk.

Policy makers therefore have a tool at their disposal to guide decision-making in an uncertain world. But cases of appropriation of this principle by the authorities have been rare (for example, GMOs, hormone-treated beef). It is therefore important to study the spontaneous behavior of the markets.

The objective of this research is to study determinants of market uptake of an innovation where risk to health or the environment is suspected. The focus is on the production of scientific knowledge. The empirical

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3Al32042, accessed February 2021

[2] Translation of the French Charte de l'Environnement (Art.5) : « Lorsque la réalisation d'un dommage, bien qu'incertaine en l'état des connaissances scientifiques, pourrait affecter de manière grave et irréversible l'environnement, les autorités publiques veillent, par application du principe de précaution et dans leurs domaines d'attributions, à la mise en oeuvre de procédures d'évaluation des risques et à l'adoption de mesures provisoires et proportionnées afin de parer à la réalisation du dommage. »

data is based on the case of the Japanese market of polycarbonate, a material whose manufacture requires the use of bisphenol A, a potential endocrine disrupter.

Polycarbonate is a transparent plastic material that is widely used, especially for the manufacture of CDs, DVDs, Blue-Rays, but also for some protective glass, motorcycle helmets, and until the early 2000s recently for baby bottles (Brignon and Gouzy 2010). It is very successful in terms of market longevity, but questions are raised because its production requires the use of bisphenol A (BPA), and its use may lead to releases of the substance in the environment. As to bisphenol A, it was discovered at the end of the 19th century and started being commercialized in the 1940s. It has many applications, but today it is mostly used in the production of polycarbonate (PC) and epoxy resin.

In 1993, some of the first publicly available evidence of 'unsuspected estrogenic activity' of bisphenol A was revealed by Krishnan et al. (1993). Since then, a large quantity of studies has investigated endocrine-disrupting properties of BPA. As endocrine disruptor, BPA might cause 'reduced fertility and increased progression of some diseases, including obesity, diabetes, endometriosis, and some cancer' (Yang et al. 2015, p. 1). However, conclusions differ (EFSA CEF Panel 2015; European Chemical Agency (ECHA) 2017) and are at the core of scientific controversy. There are still controversies about the effects of chronic exposure to BPA, particularly at very low doses, and public concern could therefore spread out to other types of applications of BPA use.

Precautionary measures were taken in 2008 for applications with the most obvious routes of exposure to the most sensitive populations, without a dose-response function that had been scientifically established. Canada was the first country that imposed a ban on infant feeding bottles containing polycarbonate in 2008, and it preceded the EU which limited the use of BPA in baby bottles in 2011. Several studies (Nakanishi et al. 2007; Stone et al. 2010) provide evidence that some companies started replacing BPA in plastic baby bottles voluntarily due to concerns raised by the public. Japan started the voluntary replacement of bisphenol A in the late 1990s, before an interim scientific conclusion on a point related to risk was drawn by the Japanese Committee on Health Effects of Endocrine Disrupting Substances (Nakanishi et al. 2007). The authors report that in 1998 around 300 local municipalities changed tableware made from polycarbonate used in schools and in 1999 around 500 municipalities were about to replace them[3].

[3] Additionally, the authors provide evidence that epoxy resin films were partially substituted for PET (poly(ethylene terephthalate)) films in the coating of beverage cans and PVC producers decreased substantially the quantity of BPA in the production.

The case of Japan is studied for several reasons. First, as mentioned above, Japan has a long history with BPA. Public concern and voluntary approaches have emerged very early on in this country[4], making the study of the link between the polycarbonate market and the development of scientific knowledge relevant. Secondly, and the two reasons may be related, more accurate polycarbonate sales data was available for this country than for other relevant a priori markets. Finally, the precautionary principle as such does not exist in Japanese law, and this places the burden of responsibility for selling products that are potentially harmful to health or the environment on industry, even if the latter was uncertain of their harmful impacts.

The remainder of the paper is structured as follows: section 2 draws from a literature review to introduce working hypotheses, section 3 presents the methodology, the data and the models, section 4 is devoted to the results, and section 5 discusses the findings and concludes.

2. Literature review and working hypotheses

Innovation can be seen either as a contributor to environmental degradation or as a solution to different environmental problems (Tidd and Bessant 2013), and both approaches have produced a large literature. This work draws on the empirical literature on the Environmental Kuznets Curve, a model which presents an inverted-U-shaped link between economic growth and environmental degradation (Dinda 2004). Environmental degradation increases as income per capita increases up to a threshold where the environmental degradation decreases with higher income (Dinda 2004; Grossman and Krueger 1995; Katz 2015; Stanchi 2014). If the environment is considered as a normal good, increase in income may boost higher environmental expenditure and environmental regulations (Dinda 2004; Smulders and Bretschger 2000). As income increases, people become more concerned about the environment and health, which might put more pressure for environmental and health regulations (Dasgupta et al. 2002; Dinda 2004; Ghimire and Woodward 2013).

The theoretical framework behind the empirical studies on the Environmental Kuznets Curve can be based on a simple one-sector model that entails the consumption of a product and an abatement of its side-product. The model of Andreoni and Levinson (2001) begins with the idea that an agent maximizes utility that depends on the consumption of one good and its byproduct that is pollution. The byproduct depends positively on consumption and negatively on the “environmental effort” that is a pollution reduction effort (Andreoni and Levinson 2001, p. 271). The maximization is subject to resource (income) constraint that can be expended on

[4] Potential risk of bisphenol A reinforced a negative public attitude towards chemicals which had been formed earlier as a result of dioxin pollution. Dioxin emissions originating from a large quantity of waste incinerators in Japan had turned society’s attention to endocrine disrupting chemicals (Malisch and Kotz 2014; Tajimi et al. 2005).

consumption and pollution abatement/prevention. Using Cobb-Douglas framework (abatement function), the authors show that an inverted U-type relationship between income and pollution/side-product/environmental degradation is possible if pollution abatement has increasing returns to scale. The authors explain the Environmental Kuznets Curve (EKC) by a technological relationship between consumption and pollution given that consumption is a source of pollution and pollution abatement spending improves the situation. If abatement exhibits increasing returns to scale, high-income agents can consume more with fewer side-effects. At a higher level of income, a society has a greater ability to abate the impact of environmental degradation.

Different variables, like natural resources use, material and energy flows can be used as proxies of environmental degradation (Katz 2015; Sun and Fang 2018; Vehmas et al. 2007). More recently, several authors (Kamoun et al. 2017; Tiba and Frikha 2019) have used adjusted net savings as a proxy for sustainability to test a modified Environmental Kuznets Curve. In this paper the consumption of a potentially harmful material is used instead of pollution indicators to test the EKC given the use of BPA/polycarbonate can entail environmental and health issues. Sriram et al. (2014) indicate that consumption of bisphenol A is affected by demand for epoxy resin and polycarbonate which are in turn influenced by the 'overall health of the economy'. The consumption of bisphenol A or polycarbonate can be responsive to changes in economic growth, there is no evidence that this relationship holds in the long run. Delinking of polycarbonate use from economic growth is examined.

Another stream of literature focuses on the intensity-of-use hypothesis which can be explained by the availability of natural resources, improvements in the efficiency of material use and/or shift towards the service sector. Several studies have showed an inverted-U pattern between material use (steel, copper and aluminum) and income (Crowson 2018; Dinda 2004; Evans 2011; Huh 2011; Wårell 2014). However, results vary significantly across countries. Domestic material consumption is one of the indicators that can be used in the analysis to study the relationship between material use and economic development (Vehmas et al. 2007). The intensity of material use can be low when income per capita is low, and it might increase at later stages of economic growth up to a threshold where it can start decreasing with increase in income per capita. At higher level of economic growth coupled with environmental consciousness, the consumption of potentially harmful material can decrease.

This paper adds to the literature on the EKC and potentially harmful materials, which remains relatively limited. This has been explored in prior studies by Ghimire and Woodward (2013), for example. There, the authors study the relationship between pesticide use and macroeconomic variables in addition to climate and agronomic variables.

New technologies can offer great benefits to society, but they could pose serious environmental and health risk. Their side-effects might be unknown in the early stages of a product life cycle, or uncertain later in the life cycle. It can be expected that in both cases increasing scientific evidence of the potential undesirable effect of a product might have an effect on the rise of public concern, and ultimately on the diffusion of the product. Increasing scientific knowledge about potential risk of BPA and controversy that goes with this issue might impact the consumption of polycarbonate A in the long run. This working hypothesis about new scientific knowledge is consistent with the literature on the Environmental Kuznets Curve. Bimonte (2002) states that a higher level of information access may increase demand for environmental quality.

It can also be considered as coherent with the precautionary approach. As already mentioned, the precautionary principle requires that measures should be all the more stringent as the consistency of the scientific dossier is high. Reasons for acting/not acting in a certain way should be based on available knowledge while research is one of the available tools (Sunstein 2005). If the reasoning is transposed to companies, it is expected that companies adapt the diffusion of their products accordingly, and that the more harmlessness is questioned by scientists, the less they diffuse their products.

This hypothesis is supported by a model of impact for unfortunate events. According to this model, the public response to an unfortunate event depends on the spread of impacts which in turn depends, among other things, on such characteristics related to risk as perceived lack of control, novelty, etc. (Slovic 1987). Although in general terms not all scientific knowledge can be considered as an unfortunate event, yet the discovery of a potential risk can be considered as an unfortunate event which might lead to loss of sales, community opposition, etc. following a similar pattern.

New knowledge can be considered difficult to transfer and measure (Kafouros 2008; OECD/Eurostat 2019). Hence one of the issues to tackle is how to properly measure new scientific knowledge about risk. According to the literature several proxies can be used. The choice of which proxies to use to measure knowledge depends on the specific needs of the study (OECD/Eurostat 2019).

The main measures of science and innovations are the past and current R&D expenditure and the number of patents (Kafouros 2008; Mairesse and Mohnen 2010). As new knowledge may generate innovations, Hall et al. (2010) highlight that R&D expenditure is an input in the process of innovation and there is a time lag from expenditure to innovations. Patents can be “an output of the knowledge production function with R&D as an input, and an input to the production function to explain a firm’s performance, such as productivity”

(Nagaoka et al. 2010, p. 1105). Besides, data on knowledge that results in innovations can be useful to deal with outcomes related to market share, sales, employment, profit, etc (OECD/Eurostat 2019).

Porter and Detampel (as cited in Ávila-Robinson & Miyazaki (2013)) use the term “bibliometrics” to refer to “publications, patents and/or their citations targeting the measurement and interpretation of scientific and technological advances”. Papers published in scientific journals can be used to measure knowledge acquired from academic research (Zahringer et al. 2017). Academic knowledge can be seen as an external input to the production function (Zahringer et al. 2017). Data on articles or patents can be considered as an output of the knowledge production function.

Patents and scientific articles can be substitutes if scientists have to choose between publishing and patenting given the time constraint. However, it has been suggested that they can be complements and patents may have a positive impact on publications (Stephan 2010).

In the case of polycarbonate, we are interested in the findings of scientific research about risk which deals with toxicological properties (hazard), which are not necessarily patented. Besides, the link between patents and risk to health or the environment is not clear. Regarding the R&D expenditure, it is very difficult to obtain the data on the expenditure on R&D related to polycarbonate or BPA at international level. The overall expenditure on R&D may give misleading results, as this indicator does not show the true level of expenditure related to BPA. Besides, the part of expenditure devoted to BPA may change over time. R&D expenditure and patents are not well suited to our purpose. Another bibliometric indicator, namely scientific publications, seems to be the most appropriate for our study because as discussed in a later section, the scientific literature remains a primary channel of information concerning potential risk.

Another stream of literature focuses on research publications in scientific and technical journals and uses these publications as an R&D/innovation indicator. For example, scientific articles cited within “the world’s most highly cited patents” can be used as a proxy for R&D (Tijssen and Winnink 2018, p. 689). According to Caliari and Chiarini (2016) there is a bidirectional relationship between knowledge production and GDP per capita. The authors argue that a rise in the stock of knowledge may have a positive effect on GDP per capita and that economic development may have an impact on knowledge production depending on the absorptive capacity. In addition, Amirat and Zaidi (2019) have found that scientific and technical journal articles, which can be considered as knowledge-based economy indicators, have a positive effect on GDP growth. The principal hypothesis of this study is that changes in polycarbonate consumption are associated with changes in the number of scientific articles relating to BPA knowledge. However, although this working hypothesis is consistent with the argument that scientific knowledge has a positive effect on GDP per capita, the study of this link is beyond the scope of the paper.

In view of the literature mentioned above, the working hypothesis to be tested is that the increasing quantity of new scientific knowledge on risk negatively impacts the diffusion of innovation in a situation of uncertainty about environmental and health risk. In other words, the higher the quantity of scientific knowledge about risk related to a product, the lower the sales of this product. With regards to the specific case of BPA, the quarterly number of scientific articles examining its toxicity is constantly growing (Fig. 1).

[Figure 1 near here]

The conclusions of research papers on risk diverge significantly. Some papers conclude that there is a potential risk associated with BPA to health and the environment while others conclude that there is no potential risk. Sometimes, the research findings are inconclusive. The ongoing controversy is further fueled by the divergence of conclusions. For example, over the 1960-2013 period, 1468 articles related to potential risk of BPA were published. Several rounds of search were run containing keywords such as "epidemiology", "toxicity" and "endocrinology" together with "bisphenol A" or "BPA". 1468 abstracts are manually analyzed covering the 1960 – 2013 period and assigned to three groups, namely 'Risk', 'No risk' and 'Uncertain'. The first group 'Risk' consists of abstracts on potential risk/danger to health/environment associated with bisphenol A (BPA). The second group "No risk" is composed of the abstracts concluding that there is no potential risk to health/environment associated with BPA. The third group 'Uncertain' comprises the abstracts with inconclusive findings[5]. Over the 1960-2013 period, a cumulative number of papers classified under groups 'Risk', 'No risk' and 'Uncertain' is 464, 120 and 334, respectively (Fig. 2).

[Figure 2 near here]

Despite the growing number of scientific publications related to the potential risk of bisphenol A (BPA), the link between new scientific knowledge of potential BPA risk, economic growth and consumption of a secondary intermediate good containing BPA, namely polycarbonate (PC), is poorly documented. More generally, to the best knowledge of the authors of this study, apart from rare work like Carayannis and Campbell (2010), there is very little documentation to help understand the links between the production of new scientific knowledge about risk and innovation uptake in a situation of uncertainty. Therefore, the study should contribute an important brick of knowledge to the topic.

[5] In order to detect a potential interpretation bias, the abstracts were re-reviewed through a short questionnaire assessing how a sample of abstracts is interpreted by others. None of the participants had an expert knowledge of BPA risk/danger before completing this questionnaire.

A large literature studies the relationships between new knowledge about health risks and the consumption of final goods. For example, some early empirical studies have shown that there is a link between health and safety concerns (even if they are not always scientifically grounded) and food consumption for several food categories (Moon and Ward 1999; Van Ravensway and Hoehn 1991). In contrast to these findings, Kenkel and Chen (2000) review a set of literature over the 1954-1991 period focusing on demand for tobacco, and the authors present several studies indicating no effect or only a slight reduction in demand as a result of the publication of new information on the health effects of tobacco (Kenkel and Chen 2000). Yet all these studies deal with consumer goods that are final goods. In this context it is part of the originality – and value – of our own work to establish a method to analyze the relationship between the production of new knowledge and the consumption of an industrial intermediate good. It does so by focusing on relationship between polycarbonate sales and the number of scientific articles.

3. Methodology

Datastream's quarterly data on sales value of polycarbonate and producer price index (PPI) of polycarbonate are used to analyze the relationship between polycarbonate sales in volume at constant prices, GDP per capita (GDPc) in Japan, its quadratic term, together with the number of scientific articles related to BPA risk and its quadratic term. The Autoregressive Distributed Lag (ARDL) procedure is applied to test the validity of the Environmental Kuznets Curve (EKC) hypothesis. Then, the relationship between polycarbonate consumption, economic growth and new scientific knowledge about risk in a situation of uncertainty about this risk is estimated.

3.1. Data

The impact of income and that of the number of new scientific publications related to risk of bisphenol A on polycarbonate consumption in Japan is studied using quarterly data on sales value of polycarbonate, its price index, Gross Domestic Product (GDP) per capita, its quadratic term and the number of publications for the following period: 1990:Q1 – 2019:Q1. Since PC sales and new scientific knowledge diffusion processes deal with time, the time series analysis is appropriate for depicting a dynamic behavior of joint movement of these variables.

3.2. Seasonality and sample construction

Datastream provides non-seasonally adjusted monthly data on the sales value of polycarbonate in Japanese Yen, and the domestic producer price index for polycarbonate (PPI, index, 2015=100) in Japan. Besides, Datastream gives seasonally adjusted quarterly data on Gross Domestic Product (constant prices, seasonally adjusted Japanese Yen, 2011 Chained Prices) in Japan. The choice of the variables is based on the empirical literature on the Environmental Kuznets Curve (EKC), the Precautionary Principle (PP) and a model of impact for unfortunate events.

Given that PPI data is available since 1990, all datasets are extracted over the period of 1990-2019. The number of publications is initially available on a monthly basis. Therefore, the quantities of articles related to the potential risk of BPA are converted to a quarterly basis as GDP is available on a quarterly basis. Total quarterly sales value and mean quarterly PPI are constructed as well. Seasonal adjustment (SA) for quarterly sales value was carried out given that many economic time-series possess seasonal patterns[6]. The test for seasonal adjustment was carried out prior to the seasonal adjustment using JDemetra+[7].

[Figure 3a and Figure 3b near here]

Fig. 1, Fig. 3a and Fig. 3b show the quarterly data on 3 variables, namely the number of scientific articles, seasonally adjusted quarterly sales value of PC and seasonally adjusted quarterly GDP per capita.

The preliminary evaluation of data series shows the existence of a structural break (a sudden change in 2008-2009 which corresponds to the Great Recession of 2008-2009) which may lead to structural changes in the process. The test of structural change for the potential break date is conducted and the stability of estimates is tested using a cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ).

Fig. 1, Fig. 3a and Fig. 3b also suggest the existence of a unit root for all variables of interest. Formal tests for stationarity of time-series using the augmented Dickey-Fuller and Phillips-Perron tests are conducted further for the period from 1990 to 2019.

Given the unavailability of polycarbonate sales in volume, quarterly sales values are transformed to sales in volume at constant prices (2010). A quarterly Producer Price Index (PPI) is used to eliminate a direct effect of changes in prices on sales value and computes sales of polycarbonate in volume at constant prices at time t ($Sales_t$):

$$Sales_t = (Sales\ value_t * 100)/PPI_t = P_{2010} * Q_t \quad (1)$$

[6] Several authors (Milanovic et al. 2015; Shi et al. 2014) observe variations in BPA concentrations in surface water over the seasons which might be explained by changes in human activity, which suggests the need to account for a possibility of seasonality.

[7] https://jdemetradocumentation.github.io/JDemetra-documentation/, accessed July 2019

where $Sales\ value_t$ is a sales value of polycarbonate at time t, PPI_t is a PPI at time t, P_{2015} is a price of polycarbonate at period t with reference to 2015 and Q_t is sales of polycarbonate. $Sales_t$ per capita is computed by dividing $Sales_t$ in Japan by the average population[8] at time t (million people).

Fig. 4 presents a locally weighted smoothing scatter plot of seasonally adjusted GDP per capita on the log scale and sales of polycarbonate per capita on the log scale. A preliminary data analysis suggests that the relationship between centered GDP per capita (GDPc) on the log scale and sales of polycarbonate per capita on the log scale is nonlinear. Besides, Fig. 4 suggests that the analysis with squared term only can be conducted avoiding the cubed term given the shape of the relationship. Data on the logarithmic scale is used in the analysis. [Figure 4 near here]

3.3. New scientific knowledge: variable construction

Whereas various sources of information that might affect the consumption of polycarbonate are available nowadays, the scientific literature remains a primary channel of information concerning potential risk. Scientific reports on bisphenol A are accessible online through the publications of biomedical journals. What is more, scientific findings are communicated through different media channels when an issue turns into a social problem (Jin and Han 2014). Besides, different governmental, social and political institutions may provide some information related to health which explains the link between institutional quality, environmental degradation and health status (Dhrifi 2018).

Some of the mass media (the press) also encourage the public to go further than the articles they publish and to visit scientific databases for confirmation of their arguments or for fact-checking. For example, PubMed[9] provides citations for a large quantity of life science and biomedical studies from the MEDLINE database and other scientific journals.

Data on scientific BPA reports was collected from the PubMed website which can be accessed directly by different stakeholders. The number of scientific articles is analyzed as they are accessible worldwide and published in English[10] [11]. The number of these reports available over the studied period serves as a proxy for available information to producers and final consumers of products containing BPA on the potential risk of BPA. Therefore, the constructed variable is suitable for the analysis.

[8] Extracted from Datastream, July 2019 ("[Dataset] Datastream")
[9] http://www.ncbi.nlm.nih.gov/pubmed
[10] The assessment of the publications' quality is beyond the scope of this study. It can be anticipated that potential and existing consumers can be affected by the number of published scientific articles about a specific topic.
[11] It is assumed that articles published in English represent the current state of knowledge concerning BPA. One of the possible limitations is an understanding of scientific articles published in English as the percentage of English speakers varies from country to country.

. BPA is a measure of scientific knowledge about the potential risk of BPA as all these articles together contribute to controversy. The variable 'BPA' is transformed in logarithm adding 1 to the data prior to transformation. To avoid a perfect collinearity between GDP per capita on the log scale and its squared term, a mean centering is performed.

3.4. *Descriptive statistics*

Table 1 provides summary statistics and description of the variables employed in the sample over 1990: Q1 – 2019:Q1. The lowest sales are observed in the first quarter of 2009 and the highest ones are observed in the third quarter of 2002. The lowest GDP per capita is documented in the first quarter of 1990 and the highest one is observed in the first quarter of 2019.

Table 1. Summary statistics of the key variables on the log scale, 1990:Q1 – 2019:Q1

Variable	Obs	Mean	Std. Dev.	Min	Max	Description
Log(Sales)	117	12.35	0.208	11.68	12.75	Log of sales of polycarbonate in volume at constant prices (2015) per capita[12] (per million people)
Log(GDPc)	117	6.73e-11	0.0689	-0.155	0.131	Log of GDP per capita centered on mean
Log(BPA)	117	2.525	1.439	0	4.7	Log of the number of scientific articles

Source: Authors, based on Datastream and PubMed

As highlighted previously, visual analysis of the untransformed data on the natural scale shows that each variable is nonstationary. The test results of the augmented Dickey-Fuller, Phillips-Perron of data on the log scale suggest all series are non-stationary (Table 2). Additionally, the Zivot-Andrews test has been performed; it allows for the presence of structural breaks. The unit root tests may have a low power if structural breaks are not taken into account (Harris and Sollis 2003). The results of the test show that we cannot reject H_0: a unit root in the process at 1% level of significance for 2 variables. The results imply that 2 variables out of 5 are stationary, namely Log(GDPc), $(\text{Log(GDPc)})^2$. The timing of the structural breaks for the majority of our variables happens at the same time as the recession in 2008. The augmented Dickey-Fuller, Phillips-Perron and Zivot-Andrews tests imply that we can reject the hypothesis of the existence of a unit root at 1% level of significance for all variables in first differences. Given that some of our series on the logarithmic scales are non-stationary, we cannot exclude the possibility to have a stationary linear combination of variables.

Table 2. Stationarity tests (log scale), 1990– 2019:Q1

[12] In the analysis, sales per million people are used. However, in the discussion sales are named per capita for the sake of readability.

Variables	Augmented Dickey-Fuller, 4 lags	Phillips-Perron	Zivot-Andrews	Variables	Augmented Dickey-Fuller, 4 lags	Phillips-Perron	Zivot-Andrews
Log(Sales)	-1.706	-2.254	-4.468	ΔLog(Sales)	-6.333	-11.791	-7.169
Log(GDPc)	-0.448	-1.280	-5.934	ΔLog(GDPc)	-3.971	-9.570	-9.922
$(Log(GDPc))^2$	0.040	-3.185	-6.526	$\Delta (Log(GDPc))^2$	-4.474	-10.499	-11.686
Log(BPA)	-1.045	-1.332	-4.674	ΔLog(BPA)	-7.510	-25.156	-11.059
$(Log(BPA))^2$	0.850	-0.337	-3.412	$\Delta (Log(BPA))^2$	-6.159	-26.669	-10.694

Critical values for augmented Dickey-Fuller test are 1%=-3.506, 5%= -2.889, 10%= -2.579
Critical values for Phillips-Perron test are 1%=-3.505, 5%= -2.889, 10%= -2.579
Critical values for Zivot-Andrews unit root test: 1%= -5.57, 5%=-5.08 10%=-4.82 (allowing for break in both intercept and trend)
Source: Authors, based on Datastream and PubMed

3.5. Modelling multiple time series

3.5.1. Testing for cointegration

The pretesting of the variables on the logarithmic scales using plots and the formal tests reveal that some variables are non-stationary with different order of integration, which are I (0) and I (1). It implies that these variables can be cointegrated. In order to avoid the problem of spurious regression, a test for cointegration needs to be carried out (Harris and Sollis 2003). Enders (2004) defines cointegration as “a linear combination of nonstationary variables. These variables must be integrated of the same order.” (Enders 2004, p. 322). However, it cannot be excluded that cointegration exists when the variables are integrated of I (0) and I (1) in one model (Harris and Sollis 2003).

Many different cointegration tests have been developed since the introduction of the Engle and Granger procedure (Dong et al. 2018). For example, the Johansen methodology can be used as described in Enders (2004). In the current study, it has been decided to use the autoregressive distributed lag (ARDL) procedure to deal with the possibility of non-stationary variables in the model. This procedure can be applied regardless whether the variables are I (0) and/or I(1) (Pesaran et al. 2001). Another advantage of the ARDL procedure is that it provides ‘unbiased estimates of the long-run model and valid t-statistic’(Harris and Sollis 2003, p. 18) Moreover, the Engle and Granger procedure is not suitable for a small sample size. The application of the ARDL allows to avoid the problem of small sample bias (Harris and Sollis 2003).The Engle and Granger procedure is also not appropriate as it requires the same order of integration of variables considered in the analysis as mentioned above. The ARDL has been gaining in popularity since the articles by (Pesaran et al. 2001) and it is applied by several authors to test the EKC hypothesis (Al-Mulali et al. 2016; Alam and Adil 2019).

First, the ARDL procedure is applied for the reduced specification of the Environmental Kuznets Curve (EKC) on the logarithmic scale over the period of 1990-2019, which includes the following variables: log(Sales), log(GDPc), $[\log(\text{GDPc})]^2$. A vast number of empirical studies on the EKC use reduced-form models. A reduced-form model is considered to be useful in measuring both direct and indirect effects of economic growth (Katz 2015; Saboori et al. 2012). However, it can suffer from the omitted variable bias. Second, the ARDL procedure is implemented for the extended model on the logarithmic scale over this period, which in addition to log(GDPc) and $[\log(\text{GDPc})]^2$ includes log(BPA). Due to the unavailability of quarterly data on other industry-specific factors and a small sample size, in order to construct a parsimonious model, other potentially relevant variables are not included in the analysis (information access, trade, technological progress, other external shocks, etc).

According to Pesaran et al. (2001), the ARDL(p, q1, q2) model can be written as

$$\log(\text{Sales})_t = c_0 + \sum_{i=1}^{p} \alpha_{1i} \log(\text{Sales})_{t-i} + \sum_{i=0}^{q_1} \alpha_{2i} \log(\text{GDP}_c)_{t-i} + \sum_{i=0}^{q_2} \alpha_{3i} (\log(GDP_c))^2_{t-i} + u_t \quad (1)$$

where c_0 is an intercept term, $\alpha_{1i}, \alpha_{2i}, \alpha_{3i}$ are the coefficients of the underlying model, u_t denotes the residual term, p, q_1, q_2 are lag orders.

The first step of the ARDL methodology involves defining the lag order. Lag length can be tested using the Akaike's Information Criterion (AIC) and Schwarz's Bayesian Information Criterion (SBIC). According to Becketti (2013) and Kripfganz and Schneider (2018), the SBIC is appropriate as this criterion is likely to choose more parsimonious model. As soon as the lag length is identified, the chosen model is estimated by Ordinary Least Squares (OLS). According the ARDL bound test framework developed by Pesaran et al. (2001), the decision concerning the cointegration is based on the F-test with the null hypothesis: H_0: no cointegration. Then, the F-statistic should be compared to the critical values provided by Narayan (2005) and Pesaran et al. (2001). In addition to the bound tests, the Gregory-Hansen (GH) test is conducted given a potential existence of structural breaks. This test does not require to know the break date. Harris and Sollis (2003) state that a cointegration test that does not take a structural break into consideration has a lower power. The null hypothesis of no cointegration is tested against cointegration with a structural break (Gregory and Hansen 1996). Three different cases are tested (Harris and Sollis 2003, p. 86):

"a change in the intercept but no change in the slope [of the coefficients]"

"a change in the intercept allowing for a time trend"

"a change in the slope vector as well as a change in the intercept".

If the cointegration is established, the following model with the error-correction term can be estimated (the reparametrized version of the ARDL)

$$\Delta\log(\text{Sales})_t = c_0 + \delta EC_{t-1} + \omega_1 \Delta\log(\text{GDP}_c)_t + \omega_2 \Delta(\log(GDP_c))_t^2 + \sum_{i=1}^{p-1} \beta_{1i} \Delta\log(\text{Sales})_{t-i} + \sum_{i=1}^{q_1-1} \beta_{2i} \Delta\log(\text{GDP}_c)_{t-i} + \sum_{i=1}^{q_2-1} \beta_{3i} \Delta(\log(GDP_c))_{t-i}^2 + u_t \quad (2)$$

where $EC_{t-1} = \log(\text{Sales})_{t-1} - \theta_1 \log(\text{GDP}_c)_{t-1} - \theta_2 (\log(\text{GDP}_c))_{t-1}^2$ is the error-correction term, δ is the speed of adjustment, ω_1, ω_2, β_{1i}, β_{2i}, β_{3i} indicate short-run coefficients, Δ is a first difference operator.

Having conducted the tests, a more parsimonious model can be estimated. Additionally, the need of the inclusion of trend and/or constant terms is tested using a likelihood-ratio test of the nested against the encompassing model (Becketti 2013).

The post-estimation test is conducted to assess the model adequacy, namely test for autocorrelation in residuals, normally distributed residuals and stability of the estimates. In order to test the stability of the estimates, the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) charts are presented.

4. Results

4.1. Estimation results for the reduced model on the log scale, 1990:Q1 – 2019:Q1

The cross-correlation functions suggest that increases in the seasonally adjusted GDP per capita on the log scale today are correlated with decreases in the sales in the future. Besides, increases in the sales seem to be uncorrelated with changes in GDP (Fig. 5). Fig. 4 presents the locally weighted smoothing scatter plot of seasonally adjusted GDP per capita on the log scale and sales of polycarbonate per capita on the log scale, 1990-2019. The plot suggests the relationship is nonlinear.

[Figure 5 near here]

The first step of the ARDL methodology involves defining the lag length and carrying out a test for cointegration. First, the results of the Gregory-Hansen test are presented. The test's null is no cointegration against the alternative of cointegration with a single shift at an unknown point in time. The null hypothesis can be rejected at 1% of significance irrespective of the type of break in the cointegration vector (Table 3).

Table 3. Results of the Gregory-Hansen test

Type of break[13]	Test statistic	Breakpoint	Date	Asymptotic Critical Values		
				1%	5%	10%

[13] SBIC was used to choose the number of lags.

Break in the constant term	Zt= -6.32	71	2007q3	-5.44	-4.92	-4.69
Break in the constant and the trend	Zt= -6.82	74	2008q2	-5.80	-5.29	-5.03
Break in the constant and the slope	Zt=6.98	74	2008q2	-6.51	-6.00	-5.75

Before the ARDL bound test framework, in order to deal with a structural break, a time dummy variable that equals 1 if time is equal to or greater than 2007Q3 is added to the model. Two interaction terms are created between this dummy variable, and the following variables $\log(GDP_c)$ and $(\log(GDP_c))^2$. Having estimated the model with the error-correction term and a time-dummy variable, the hypothesis that the dummy variable in the cointegrating relationship equals 0 using a likelihood-ratio test is tested. Next, the hypothesis of no interaction term with $\log(GDP_c)$ is tested. Finally, the hypothesis that there is no interaction term with $(\log(GDP_c))^2$is tested. Eventually, based on the results of these tests, a model with a time dummy variable and without interaction terms is estimated. Lag length is tested using Schwarz's Bayesian information criterion (SBIC). It indicates the following lag length: p=1, q1 =1, q2 =0. As a result, the ARDL (1, 1, 0, 0) with the error-correction component is estimated and ARDL bound test is conducted. The results of Pesaran, Shin, and Smith (2001) bound tests indicate that the hypothesis of no cointegration can be rejected at 1% level of significance (F= 5.898).

Having estimated the ARDL (1, 1, 0, 0) model, the hypothesis that a constant term in the model equals 0 is tested using a likelihood-ratio test. Next, the hypothesis of no linear trend is tested. Finally, the hypotheses of no restrictions on the constant term or the linear trend are tested. Eventually, based on the results of these tests, a constant is included in the model. The results of the ARDL (1, 1, 0, 0) are presented in Table 4a and Table 4b.

Table 4a. Short-run results, dependent variable: Δlog(Sales)

Variables	Reduced model	t statistic
ECt-1	-0.297***	
	(0.0638)	-4.66
Δlog(GDPc)	3.921***	
	(0.725)	5.41
Δ[log(GDPc)] ²	-7.127***	
	(2.074)	-3.44
ΔTime dummy	-0.110***	
	(0.0331)	-3.33
Constant	3.736***	
	(0.804)	4.65
Observations	116	
R-squared	0.337	

Table 4b. Long-run results

Variables	Reduced model		t statistic
log(GDPc)	1.704***		
	(0.536)	0,5360435	3.18
[log(GDPc)] ²	-24.00***		
	(5.114)	5,113643	-4.69
Time dummy	-0.371***		
	(0.0733)	0,0732638	-5.06

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Source: Authors, based on Datastream and PubMed

The results of the post-estimation confirm the existence of a long-run relationship between consumption of polycarbonate and economic growth in Japan where log of GDP has a positive relation with sales of polycarbonate and the squared term of GDP has a negative relationship with sales. These results are consistent with expectations. The coefficients on the log of GDP and its quadratic terms are statistically significant at 1% level of significance. The turning point of centered logarithm of per capita GDP is 0,0355. The results support the EKC in the long-run as they show the existence of an inverted-U-shaped relationship between consumption of polycarbonate and economic growth. Given the small size of the sample, the focus is on the pattern of the relationship, but not on the precise size of parameters.

The speed of adjustment coefficient is statistically significant at 1% level of significance. It implies that sales respond to a deviation from equilibrium and correct it. The speed of adjustment suggests that the responses of sales of the previous period's deviation from the long-run equilibrium is about 30% over one quarter. Short-run coefficients are statistically significant, and the results support the EKC in the short run.

The equilibrium is achieved when

$$\log(\text{Sales}) = 1.704 * \log(\text{GDPc}) - 24.00 * [\log(\text{GDPc})]^2 - 0.371 * \text{Time dummy} \quad (3)$$

Table 5. Post-estimation tests

Durbin-Watson d-statistic	(6, 116) = 2.02495
Breusch-Godfrey LM test for autocorrelation H0: no serial correlation	0.046 (0.8301)
White's test for homoskedasticity Ho: homoskedasticity against Ha: unrestricted heteroskedasticity	χ^2 (18) = 65.36 (0.0000)
Skewness/Kurtosis tests for Normality: Pr(Skewness): 0.2129 Pr(Kurtosis): 0.0170	Joint χ^2 (2) = 6.75 (0.0342)

P-value in parentheses

Source: Authors, based on Datastream and PubMed

Post-estimation tests are presented in Table 5. The null of no serial correlation cannot be rejected. The null hypothesis of homoscedasticity can be rejected at 1% level. The model can be estimated using Newey-West standard errors in the presence of heteroscedasticity. The results with Newey-West standard errors provide similar coefficients and the statistical significance of the estimated coefficients follows the same pattern as previously (the results are not presented here). The null hypothesis that the residuals are normally distributed can be rejected at 5% level but not at 1% level. Based on skewness alone, the hypothesis that the residuals are normally distributed cannot be rejected. Additionally, a plot of the quantiles of residuals against the quantiles of the normal distribution and a standardized normal probability plot are presented. According to these plots, the residuals are approximately normally distributed (Fig. 6). Fig. 7 shows the CUSUM and CUSUMSQ charts, which show that the coefficients of the long-run coefficients are stable as the plots remain within the critical bounds of 5%.

[Figure 6 near here]

[Figure 7 near here]

4.2. Estimation results for the extended model on the log scale, 1990:Q1 – 2019:Q1

First, the relationship between sales of polycarbonate and the number of articles related to potential risk of bisphenol A (BPA) is examined by analyzing cross-correlation functions (Fig. 8). According to these cross-correlation functions, increases in the number of articles related to risk today are correlated with decreases in the sales in the future and increases in the sales seem to correlate with increases in the number of articles. The number of articles is measured at global level and economic growth is measured at national level. The locally weighted smoothing scatter plot of the number of articles related to potential risk of BPA on the log scale and sales of polycarbonate per capita on the log scale over the period 1990-2019 is presented in Fig. 9. The plot suggests the relationship is nonlinear. Therefore, the model has been extended by the number of articles related to potential risk of BPA and its squared term.

[Figure 8 near here]

[Figure 9 near here]

If the cointegration is established, the following model with the error-correction term can be estimated

$$\Delta\log(\text{Sales})_t = c_0 + \delta EC_{t-1} + \omega_1\Delta\log(\text{GDP}_c)_t + \omega_2\Delta(\log(GDP_c))_t^2 + \omega_3\Delta\log(BPA)_t + \omega_4\Delta(\log(BPA))_t^2 + \sum_{i=1}^{p-1}\beta_{1i}\Delta\log(\text{Sales})_{t-i} + \sum_{i=1}^{q_1-1}\beta_{2i}\Delta\log(\text{GDP}_c)_{t-i} + \sum_{i=1}^{q_2-1}\beta_{3i}\Delta(\log(GDP_c))_{t-i}^2 + \sum_{i=1}^{q_3-1}\beta_{4i}\Delta\log(BPA)_{t-i} + \sum_{i=1}^{q_4-1}\beta_{5i}\Delta(\log(BPA))_{t-i}^2 + u_t \quad (4)$$

where $EC_{t-1} = \log(\text{Sales})_{t-1} - \theta_1\log(\text{GDP}_c)_{t-1} - \theta_2(\log(\text{GDP}_c))_{t-1}^2 - \vartheta_3\log(BPA)_{t-1} + \theta_4(\log(BPA))_{t-1}^2$ is the error-correction term,

ω_3, ω_4, β_{4i} , β_{5i} indicate short-run coefficients, q_3, q_4 are lag orders.

The ARDL procedure is carried out together with the Gregory-Hansen test to test for the possibility of cointegrating relationships among the variables (Table 6). The null hypothesis of no cointegration can be rejected at 1% of significance irrespective of the type of break in the cointegration vector. Therefore, a time dummy and interaction terms are added to the model. Based on the results of the likelihood-ratio test tests, a model with a time dummy variable and one interaction term ($Time\ dummy * \log(GDP_c)$) is estimated.

Table 6. Results of the Gregory-Hansen test

Type of break[14]	Test statistic	Breakpoint	Date	Asymptotic Critical Values		
				1%	5%	10%
Break in the constant term	Zt= -6.78	71	2007q3	-6.05	-5.56	-5.31
Break in the constant and the trend	Zt= -6.78	74	2008q2	-6.36	-5.83	-5.59
Break in the constant and the slope	-7.83	74	2008q2	-6.92	-6.41	-6.17

Lag length is tested using Schwarz's Bayesian Information Criterion (SBIC). It indicates the following lag length: p=1, q1 =1, q2 =0, q3 =0, q4 =0. As a result, the ARDL (1, 1, 0, 0, 0, 0, 0) with the error-correction component is estimated and ARDL bound test is conducted. The results of Pesaran, Shin, and Smith (2001) bound tests indicate that the hypothesis of no cointegration can be rejected at 1% level of significance (F= 4.914). Based on the results of the likelihood-ratio tests, a constant is included in the model. The results of the ARDL (1, 1, 0, 0, 0, 0, 0) are presented in Table 7a and Table 7b. Then, the post-estimation tests are carried out.

Table 7a. Short-run results, dependent variable: Δlog(Sales)

Variables	Extended model	t statistic
ECt-1	-0.396***	
	(0.0721)	-5.5
Δlog(GDPc)	3.377***	
	(0.837)	4.04
Δ[log(GDPc)] ²	-11.11***	
	(4.074)	-2.73
Δlog(BPA)	0.0878***	
	(0.0314)	2.8
Δ[log(BPA)] ²	-0.0163**	
	(0.00739)	-2.21
ΔTime dummy	-0.166***	
	(0.0413)	-4.01
ΔTime dummy* log(GDPc)	1.737**	
	(0.751)	2.31
Constant	4.877***	
	(0.898)	5.43
Observations	113	

[14] SBIC was used to choose the number of lags.

R-squared	0.412

Table 7b. Long-run results

Variables	Extended model	t statistic
log(GDPc)	- 0.623	
	(0.979)	0.64
[log(GDPc)] ²	-28.03***	
	(8.730)	-3.21
log(BPA)	0.222***	
	(0.0728)	3.04
[log(BPA)] ²	-0.0411**	
	(0.0171)	-2.41
Time dummy	-0.417***	
	(0.0725)	-5.76
Time dummy* log(GDPc)	4.380**	
	(1.738)	2.52

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Source: Authors, based on Datastream and PubMed

The long-run results show that the coefficient on the log of GDPc is statistically insignificant and its quadratic term is statistically significant at 1% level of significance suggesting that the relationship is curvilinear. The relatively large standard errors (and as a consequence, the small t statistic) can be associated with multicollinearity, especially in a small sample. Meanwhile, we have centered GDPc in order to reduce multicollinearity. The coefficients on the log of BPA and its quadratic term are statistically significant at 5% level of significance. The results demonstrate an inverted-U pattern between consumption of polycarbonate and the number of articles on BPA in the long run. The turning point of logarithm of BPA is 2,7 (which corresponds to about 14 articles). As the number of publications stays relatively low, an additional article has a positive effect on sales of polycarbonate. However, this effect is relatively small. At some point, the effect becomes negative.

The results support the hypothesis that the changes in polycarbonate consumption are associated with changes in the number of scientific articles. Contrary to our expectations, the sales of polycarbonate initially increase with the growing quantity of scientific knowledge about risk. However, there is a threshold level beyond which the sales of this product decrease with higher quantity of scientific knowledge about risk related to this product.

The speed of adjustment coefficient is statistically significant at 1% level of significance. It implies that sales respond to a deviation from equilibrium and correct it. The speed of adjustment suggests that the response of sales from the previous period’s deviation from the long-run equilibrium is about 40% over one quarter.

Short-run coefficients are statistically significant, and the results support the EKC and an inverted-U pattern between consumption of polycarbonate and the number of articles on BPA in the short run.

Table 8. Post-estimation tests

Durbin-Watson d-statistic	(9, 113) = 1.986485
Breusch-Godfrey LM test for autocorrelation H0: no serial correlation	0.005 (0.9420)
White's test for homoskedasticity Ho: homoskedasticity against Ha: unrestricted heteroskedasticity	χ^2 (37) = 64.83 (0.0031)
Skewness/Kurtosis tests for Normality: Pr(Skewness): 0.9672 Pr(Kurtosis): 0.0545	Joint χ^2 (2) = 3.79 (0.1506)

p-value in parentheses
Source: Authors, based on Datastream and PubMed

Post-estimation tests are presented in Table 8. The null of no serial correlation cannot be rejected. The null hypothesis of homoscedasticity can be rejected at 1% level. The model can be estimated with Newey-West standard errors in the presence of heteroscedasticity. The results show that the statistical significance of the estimated coefficients follows the same pattern as previously (the results are not presented here). The null hypothesis that the residuals are normally distributed cannot be rejected. Additionally, a plot of the quantiles of residuals against the quantiles of the normal distribution and a standardized normal probability plot are presented. According to these plots, the residuals are approximately normally distributed (Fig. 10). The CUSUM and CUSUMSQ charts presented in Fig. 11 show that the long-run coefficients are reasonably stable as the plots almost remain within the critical bounds of 5%.

[Figure 10 near here]

[Figure 11 near here]

5. Discussion and conclusions

This section discusses the main findings of the study with their possible implications, some limitations of the paper, and potential further questions. The study was designed as a first attempt to assess linkages between scientific knowledge and innovation uptake in a situation of uncertainty about environmental and health risk. As well as contributing to the existing literature on the knowledge economy, the paper brings counter-intuitive elements to the understanding of the diffusion of innovation. This may prove particularly helpful to high-tech entrepreneurs and policy makers.

Drawing from the Environmental Kuznets Curve (EKC) theory, the paper empirically examines the effect of economic growth and new scientific knowledge on polycarbonate sales in Japan. By doing so, it also addresses the issue of potential lack of stationarity in the data that is often identified as a limitation in the EKC literature (Stern 2004).

5.1. Key results and implications

The growing concerns over endocrine-disrupting properties of BPA resulted in a large number of scientific publications about BPA risk and in bans on its use in several products in several countries afterwards. These bans mainly concern applications that have a wide exposure for sensitive populations, mainly infants. Nevertheless, the uses of BPA, including polycarbonate, remain numerous and are likely to be questioned by public authorities (*e.g.* thermal papers whose use is restricted by the REACH regulation), by consumers who are aware of the low-dose toxicity of the substance, or by industrialists who would anticipate one or other of these challenges.

This paper empirically examines the effect of economic growth and new scientific knowledge on polycarbonate sales in Japan. Concerning economic growth, the reduced model confirms the existence of an inverted-U-shaped relationship between economic growth and polycarbonate consumption in the long run. This result remains true in the extended model in the short run, but the coefficient of economic growth is not significant in the long run whereas its quadratic term is negative and significant in the long run. The results confirm that there is a curvature in the relationship between polycarbonate sales and economic growth. The speed of adjustment in the reduced-form model suggests that the response of sales from the previous period's deviation from the long-run equilibrium is about 30% over one quarter.

In general terms, these results are consistent with the EKC hypothesis as long as it is reasonable to assume that input/material use can be considered as an indicator of environmental degradation in a similar way to pollution. However, differences between these indicators might exist. They might concern capacity constraint or pricing (Katz 2015). There is almost no capacity constraint related to bisphenol A in the production of polycarbonate over the studied period (Sriram et al. 2014). Thus, it can be expected that there is no capacity constraint of polycarbonate over the studied period. Besides, polycarbonate can be considered as relatively price inelastic. In case of market turbulence polycarbonate can easily be put in storage until prices stabilize (Jiang et al. 2015). Therefore, polycarbonate consumption is little affected by the price of polycarbonate and it can be expected that this determinant is not crucial in the analysis. Besides, findings are consistent with previous results in the EKC literature that studies the link between different material use (copper, aluminium and steel) and GDP in Japan (e.g. Crowson 2018).

As a first attempt to study the link between new scientific publications related to potential risk of BPA and polycarbonate consumption, the number of scientific articles related to risk of BPA was used to measure availability of information on potential risk of BPA. Preliminary analysis (cross-correlation functions) suggests that increases in the number of articles related to risk today are correlated with decreases in the sales in the future. In this, a bivariate cross-correlogram does not take into account other variables (Becketti 2013).

Further investigation has revealed that both coefficients on log(BPA) and $[\log(BPA)]^2$ are statistically significant at 5% level of significance in the equilibrium equation. Furthermore, the first one is positive whereas the second one is negative which illustrates an inverted U pattern. In other words, a small number of publications is associated with an increase in polycarbonate consumption, but once a certain level is reached the material consumption decreases. This result seems to be coherent with the "precautionary thinking". The speed of adjustment suggests that the responses of sales of the previous period's deviation from the long-run equilibrium is about 40% over one quarter.

It is to be noted that a high number of publications does not mean a high degree of certainty: it is not only a proxy for scientific evidence in the sense of better-grounded scientific knowledge, but also a proxy for controversy as was mentioned before. Consequently, the results show that a relatively high number of publications, although not providing a scientific answer, may affect public acceptance.

The initial discovery of potential harmful effects might bring scientific controversy and might impact the diffusion of the product. But this study seems to illustrate the opposite in the early stages: despite the early controversy, polycarbonate sales continue to increase. Later, when ongoing scientific controversies are fueled by an increasing number of scientific reports with divergent conclusions precautionary attitudes rise. Besides, the results mean that innovation uptake is not slowed by new scientific knowledge with divergent conclusions about risk in the beginning. This result is important for entrepreneurs or venture capitalists who may want to seize opportunities related to emerging technologies or to overcome risk averseness towards founding high-tech firms in emerging technologies.

The findings may suggest that markets are waiting for consumer signals. Consumers do not react immediately to the controversy. As more improved information becomes available, consumers are able to make better decisions and they may send signals.

In this context, it can be suggested that the existence of substitutes can serve as a change lever to effect change in behavior, and that the absence of substitutes for several applications which possess similar characteristics can be compared to a lack of change lever. There are substitutes for several applications of BPA related to polycarbonate and epoxy resin, and for example glass baby bottles can be considered as substitutes for polycarbonate baby bottles together with bottles made from polypropylene. However, substitutes for other final products made with BPA like packaging and containers are not easily available over the studied period. In this case, the food and beverage companies which use BPA-free packaging will have first-mover advantage if the ban on the use of BPA in food packaging is introduced.

From a policy perspective, the findings suggest that an information disclosure alone might be an appropriate regulatory tool for policymakers in a situation of uncertainty about environmental and health risk as there is an inverted-U-shaped relationship between new scientific knowledge and polycarbonate consumption. However, more accessible public information may result in a flatter (with a lower turning point) inversed-U-shaped curve.

5.2. Conclusions

Drawing conclusions from an emerging technology of the past helps to theorize about emerging technologies of the present. This study is an analysis of the trend in consumption of a long-standing commodity. Polycarbonate is an example of a goods that has been on the market for more than 60 years. Its production requires the use of BPA, itself suspected of being toxic to humans for a long time. The initial discovery of potential harmful effects of BPA produced an ongoing scientific controversy, and this controversy is fueled by an increasing number of scientific reports with divergent conclusions. The accumulation of reports does not help to resolve the controversy but may on the contrary contribute to its development.

The goal of this paper is to study determinants of market uptake of an innovation in a situation of uncertainty regarding risk by focusing on the assessment of the relationship between polycarbonate sales and the production of scientific articles about BPA-related risk. First, the study examined the effect of economic growth on polycarbonate sales in Japan: the results confirm a curvilinear relationship between economic growth and polycarbonate consumption. Despite the rise in polycarbonate consumption due to economic growth, polycarbonate sales may decrease as a result of technological changes, preferences and/or substitution between materials. Then, the study shows that the link between polycarbonate sales and scientific knowledge about risk to health and the environment follows an inverted U pattern. As the number of publications stays relatively low, sales of polycarbonate increase up to a certain level, then sales decrease with a higher number of articles. Several explanations are possible. For example, the substitutes for some products whose production requires the use of

BPA are not easily available at the beginning of the studied period, and some substitutes are considered even more potentially risky for health or the environment than the products that they are supposed to replace.
This study gives rise to the following questions for further research:

Do the findings on new scientific knowledge about risk hold for other materials and across countries? Future studies can address the effects of new scientific knowledge about risks on other innovation uptakes in a situation of uncertainty, e.g. nanomaterials.

What other (alternate) measures of new scientific knowledge about risk can be used to estimate the relationship between polycarbonate sales and scientific knowledge about risk to health and the environment? Our paper focuses on the quantity of scientific knowledge, and the quality still remains an open issue. Some articles might have a major impact compared to other low impact articles (less well rated by scholars and governments). Further work can be done in this area, starting with indicators or measurement of quality.

Prior research suggests that a country's culture may impact the development of new scientific knowledge (Yong 2020). The production of new scientific knowledge about risk can be directly affected by a country's culture, which in turn may affect the diffusion of innovation in a situation of uncertainty about environmental and health risk. Do cultural factors explain the diffusion of innovation through the production of knowledge about risk? Other potentially relevant variables can be added in the analysis (information access, trade, technological progress, other external shocks, etc) as mentioned in Section 3.5.

In view of the above the following questions related to new products can be asked: How to manage innovations in a situation of uncertainty about environmental and health risk? What could be done differently from what was done in a case such as polycarbonate?

One promising option is the Safer by design approach (Bottero et al. 2017). With this approach that draws from both environmental science and design theory, the idea is to include – from the design stage – a life cycle analysis of the relative social and economic costs and benefits for health and the environment of material and processes used in new products. In addition to a safe and sustainable-by-design approach to chemicals (European Commission 2020), the Safer by Design methodology took off globally with the development of nanotechnology. The Safer by Design approach is one of the tools that the European Union supports with major research funding (see WG9 Safe by Design and Industrial innovation program, Safe by design NANOREG2 program, and HORIZON 2020 EU program).

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[Dataset] Datastream. (n.d.).

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Figure captions

Fig. 1 Number of scientific articles related to potential risk of BPA, 1990 – 2019:Q1. Source: Authors, based on the PubMed

Fig. 2 Cumulative number of scientific articles assigned to group “Risk”, “No risk”, “Uncertain”, “BPA”, 1990 – 2013. Source: Authors, based on the PubMed

Fig. 3a Seasonally adjusted quarterly sales value of PC, Japanese Yen, 1990-2019:Q1. Source: Authors, based on Datastream

Fig. 3b Seasonally adjusted quarterly GDP per capita, Japanese Yen, 1990-2019:Q1. Source: Authors, based on Datastream

Fig. 4 Locally weighted smoothing scatter plot of seasonally adjusted GDP per capita on the log scale and sales of polycarbonate per capita on the log scale, 1990-2019:Q1. Source: Authors, based on Datastream

Fig. 5 Cross-correlations of log(GDP) and log(Sales), 1990-2019:Q1. Source: Authors, based on Datastream

Fig. 6 Plot of the quantiles of residuals against the quantiles of the normal distribution and a standardized normal probability plot. Source: Authors, based on Datastream

Fig. 7 Plots of CUSUM (left) and CUSUMSQ (right) for the estimated ECM model. Source: Authors, based on Datastream

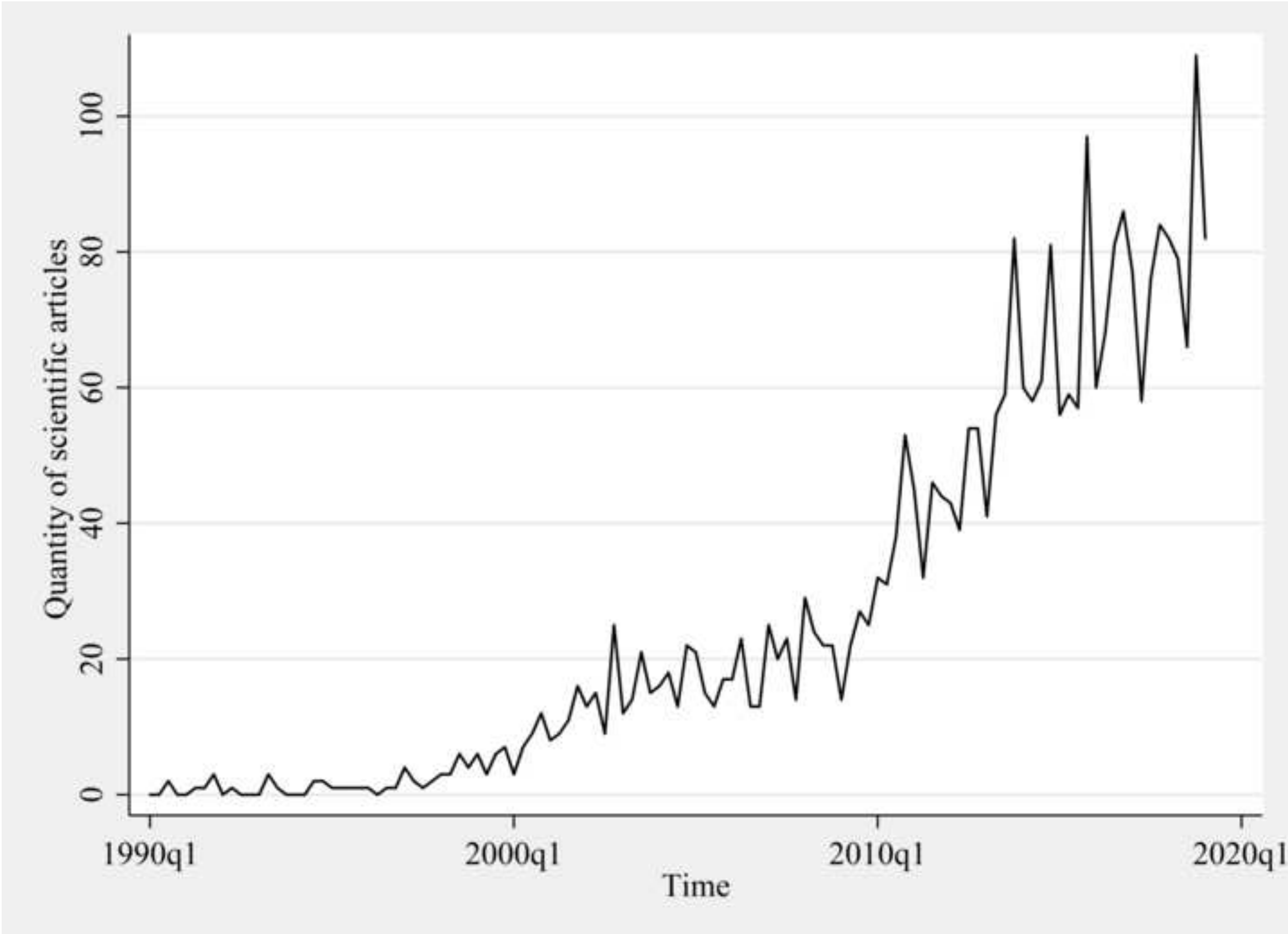
Fig. 8 Cross-correlations of log(Sales) and log(BPA), 1990-2019:Q1. Source: Authors, based on Datastream and PubMed

Fig. 9 Locally weighted smoothing scatter plot of number of scientific articles on the log scale and sales of polycarbonate per capita on the log scale, 1990-2019:Q1. Source: Authors, based on Datastream and PubMed

Fig. 10 Plot of the quantiles of residuals against the quantiles of the normal distribution and a standardized normal probability plot. Source: Authors, based on Datastream and PubMed

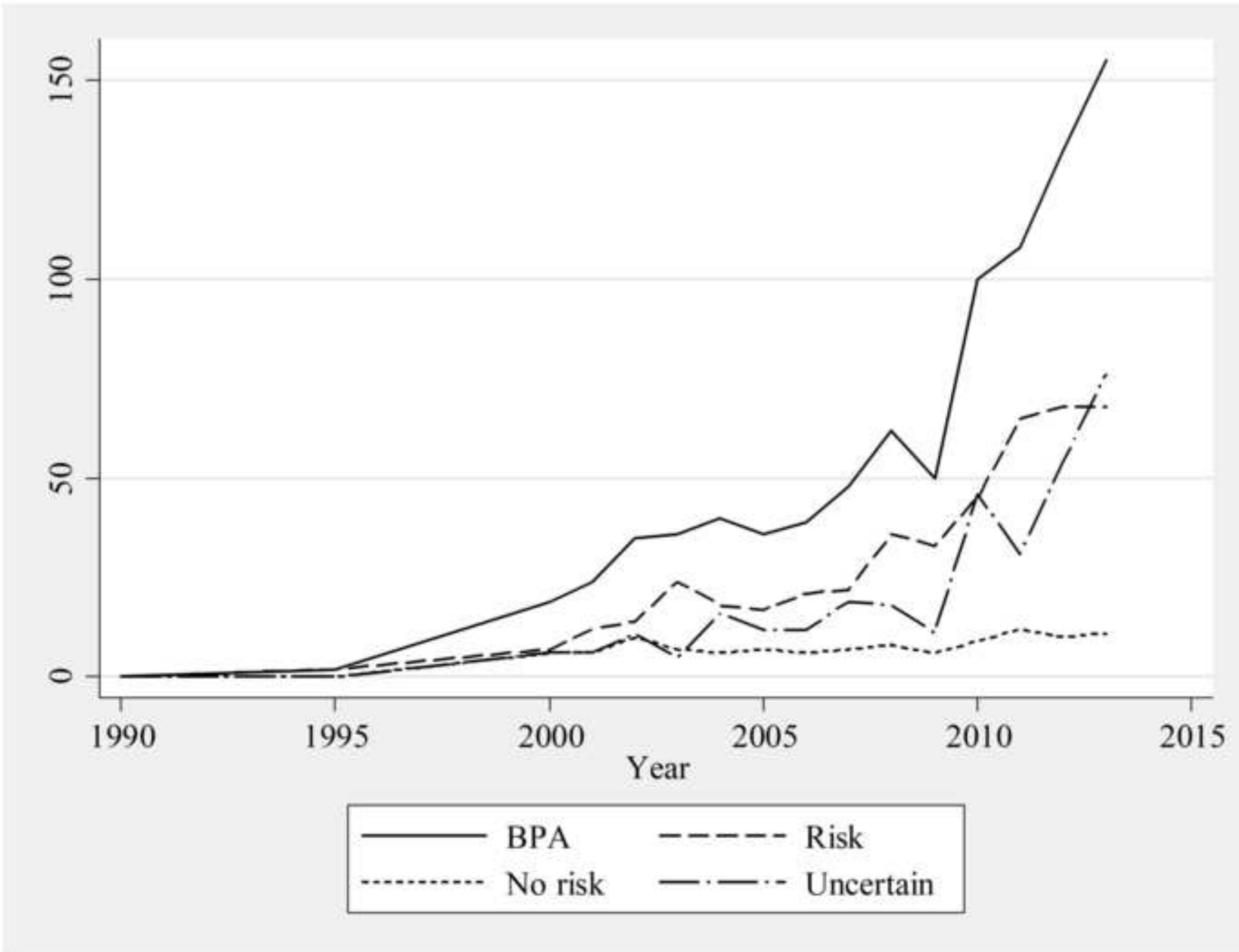
Fig. 11 Plots of CUSUM (left) and CUSUMSQ (right) for the estimated ECM model. Source: Authors, based on Datastream and PubMed

Figure 1



Quantity of scientific articles
0
20
40
60
80
100
1990q1
2000q1
2010q1
2020q1
Time

Figure 2



150
100
50
0
1990
1995
2000
2005
2010
2015
Year
BPA
Risk
No risk
Uncertain

Figure 3 (a and b)

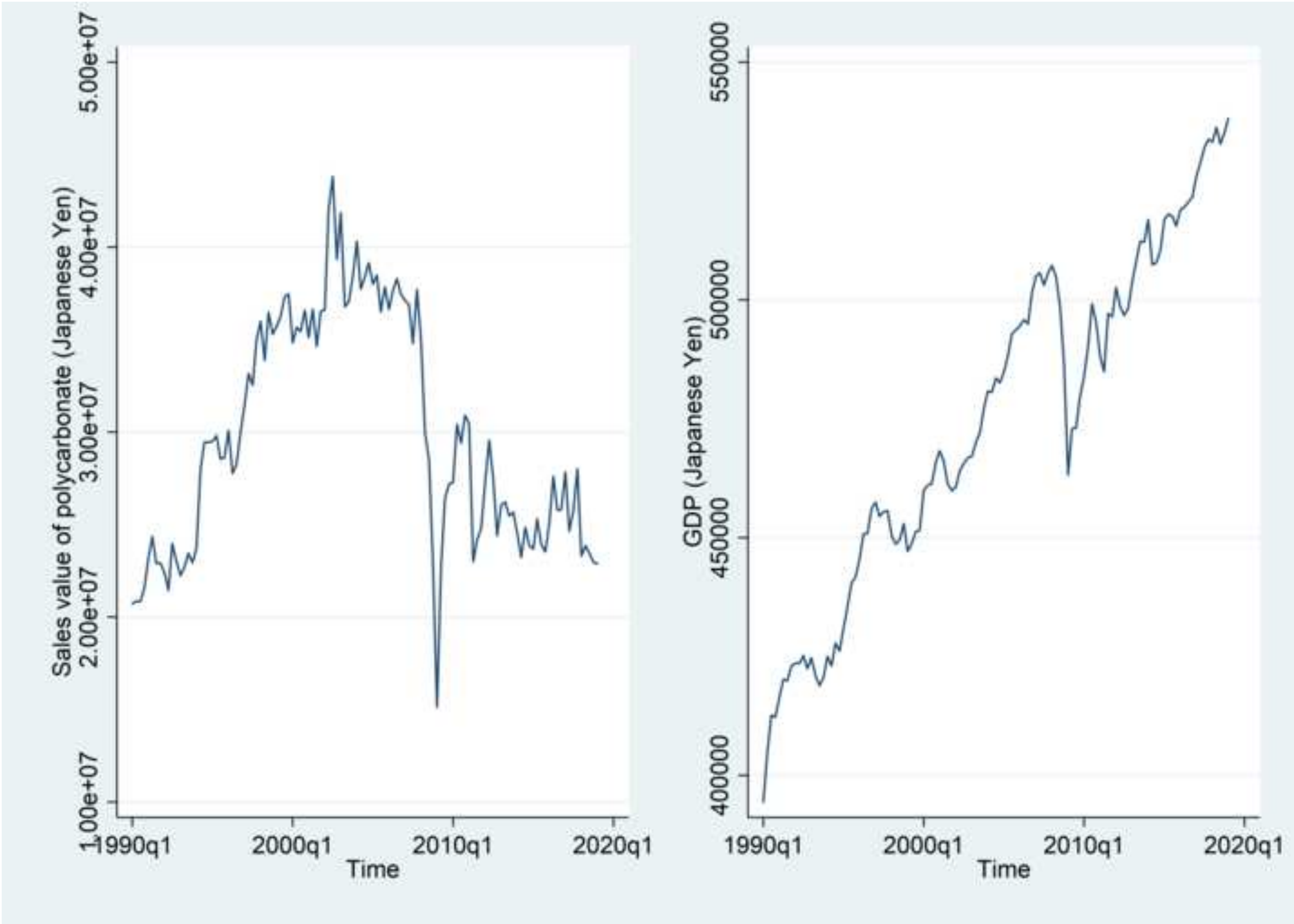


Figure 4

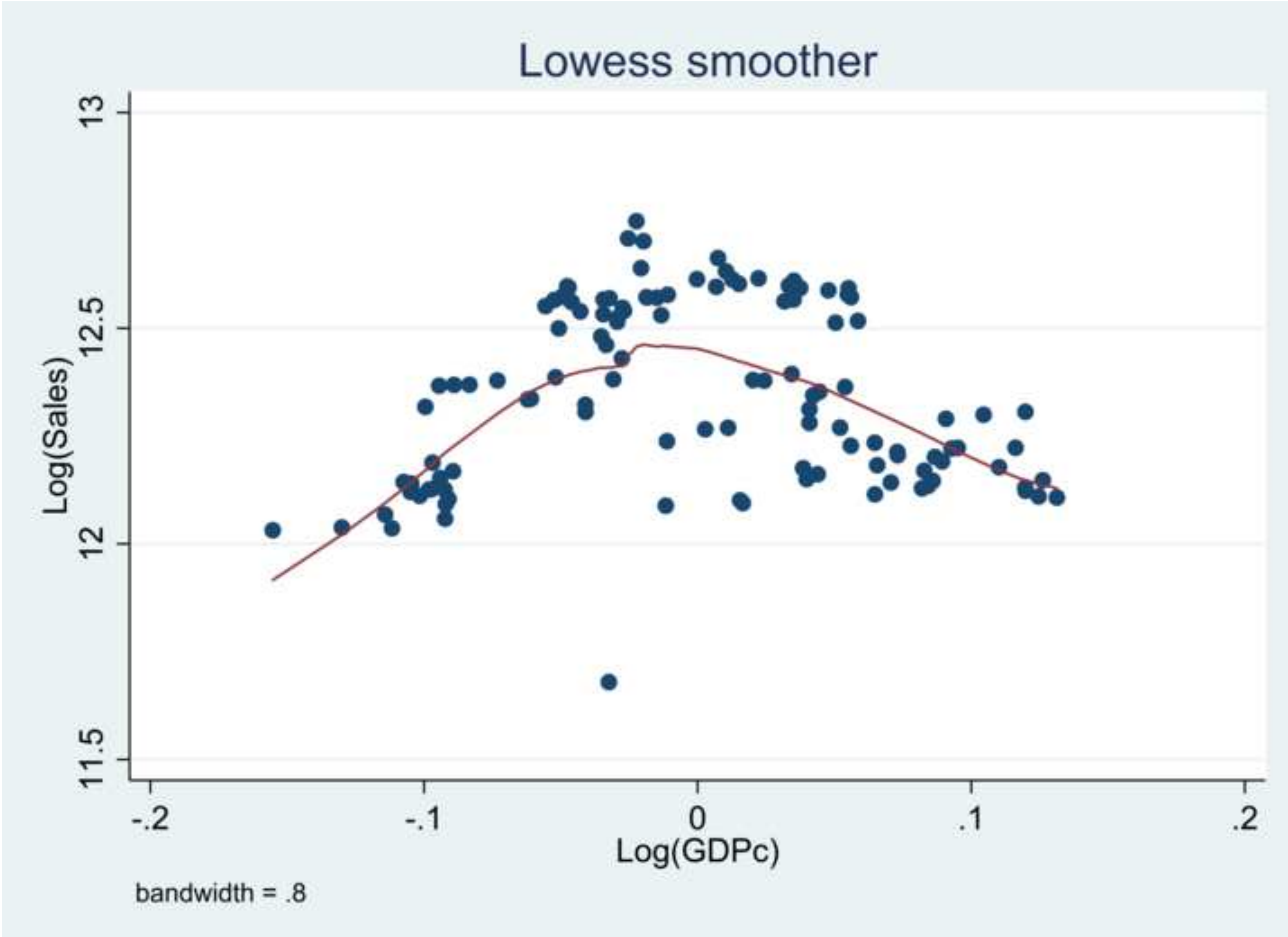
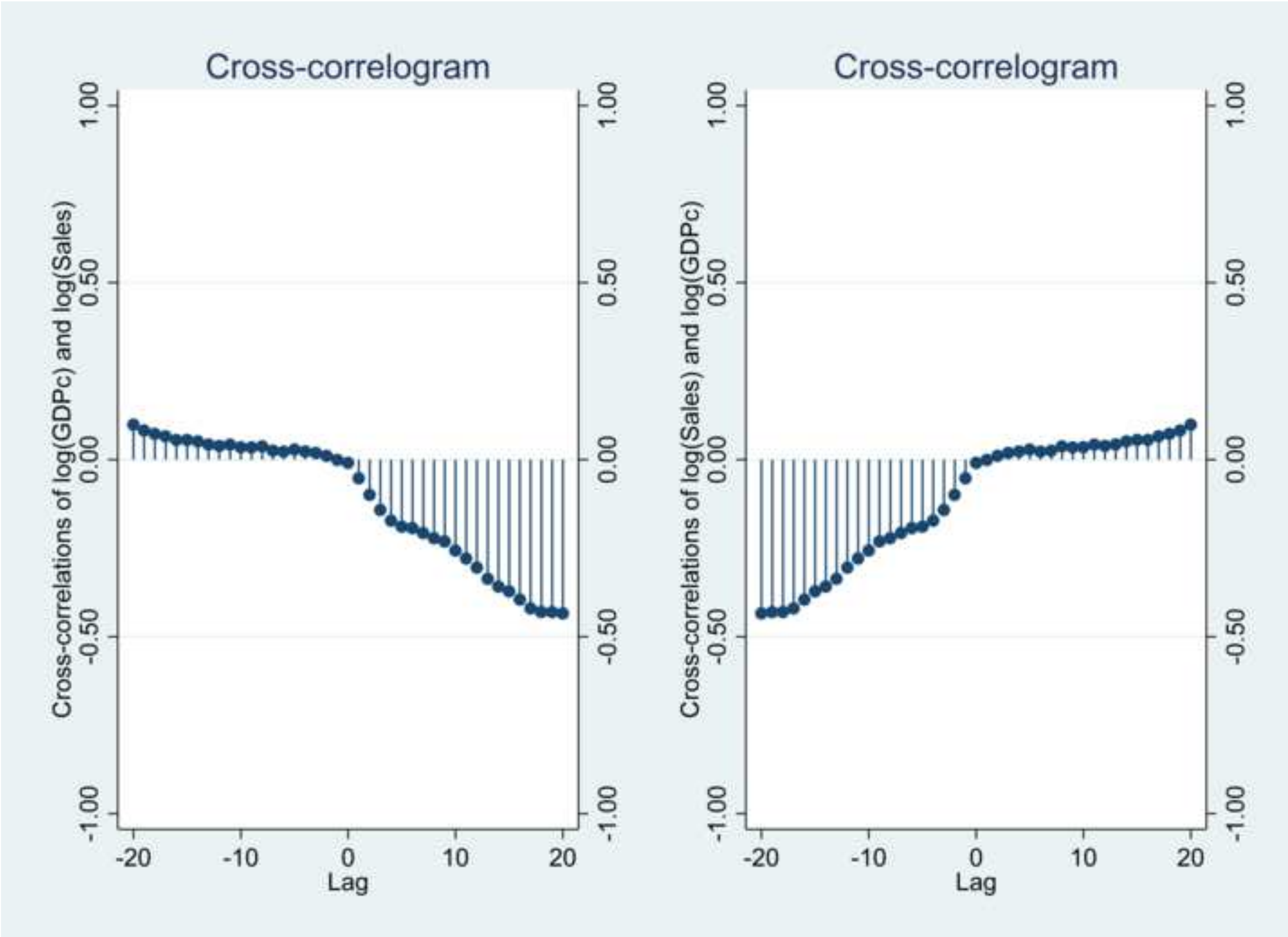
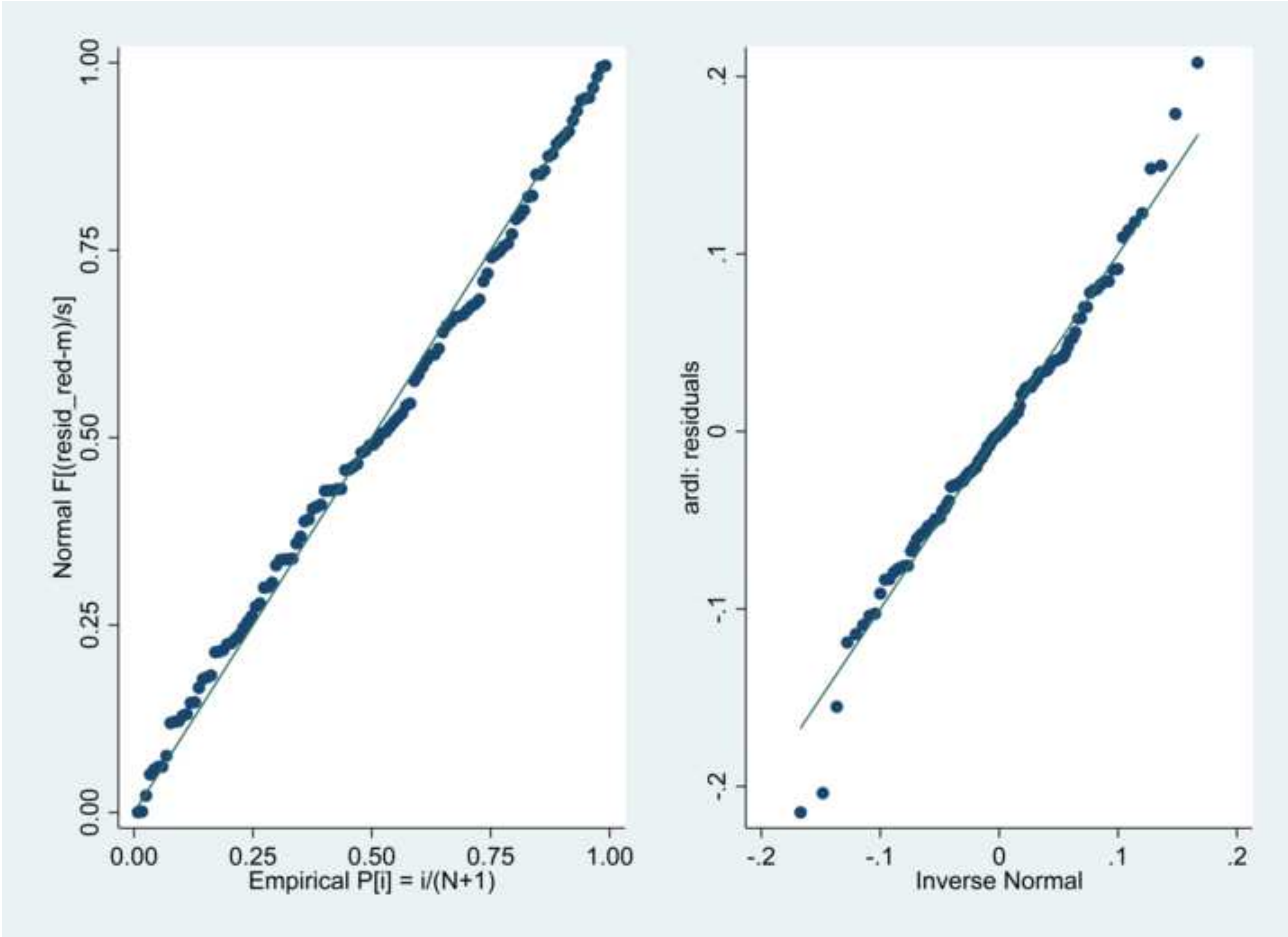

Lowess smoother
Log(Sales)
13
12.5
12
11.5
-.2
-.1
0
.1
.2
Log(GDPc)
bandwidth = .8

Figure 5



Cross-correlogram
Cross-correlations of log(GDPc) and log(Sales)
1.00
0.50
0.00
-0.50
-1.00
-20
-10
0
10
20
Lag
Cross-correlogram
Cross-correlations of log(Sales) and log(GDPc)
1.00
0.50
0.00
-0.50
-1.00
-20
-10
0
10
20
Lag

Figure 6



Normal F[(resid_red-m)/s]
0.00
0.25
0.50
0.75
1.00
Empirical P[i] = i/(N+1)
ardl: residuals
-.2
-.1
0
.1
.2
Inverse Normal

Figure 7 left

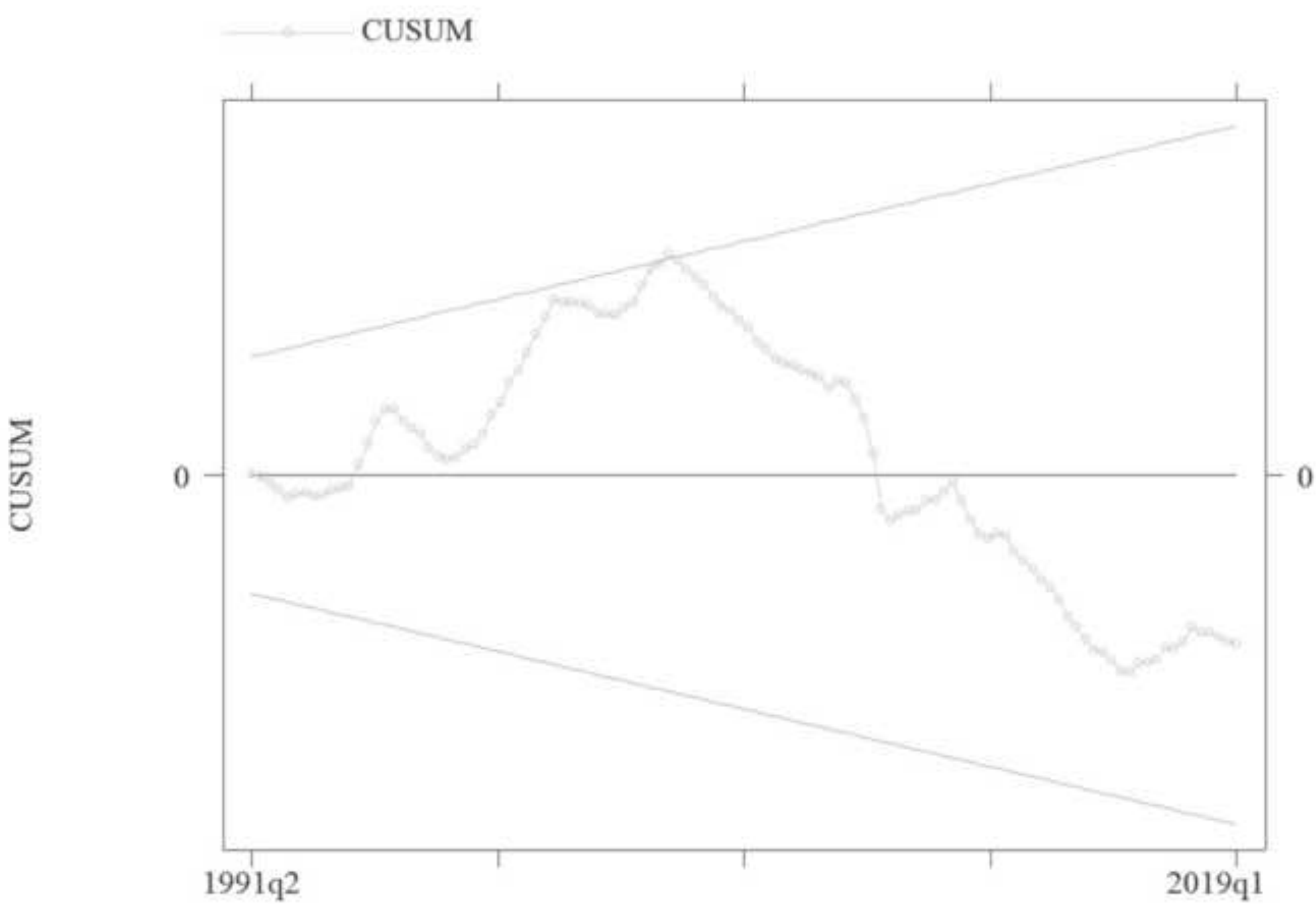


Figure 7 right

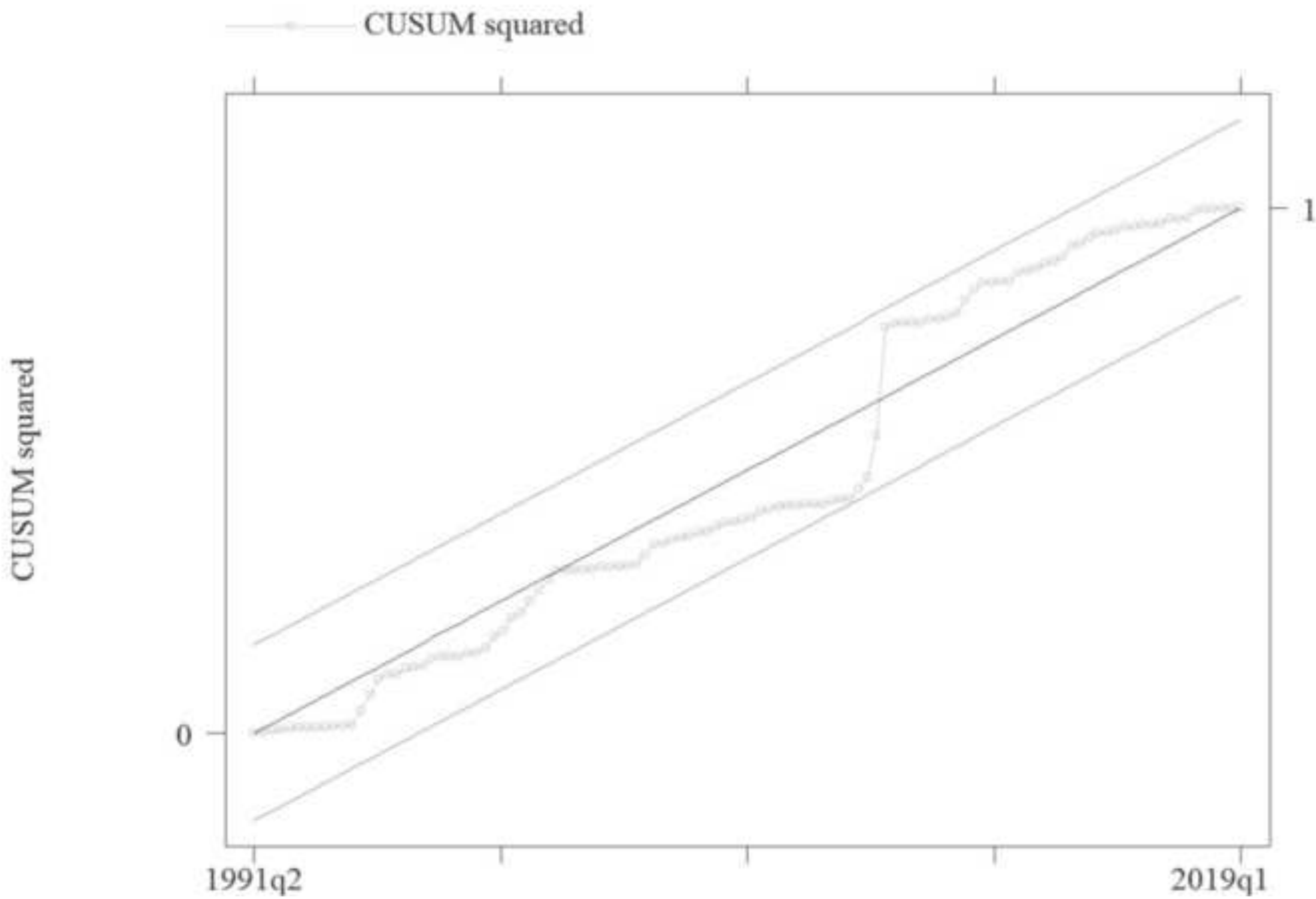
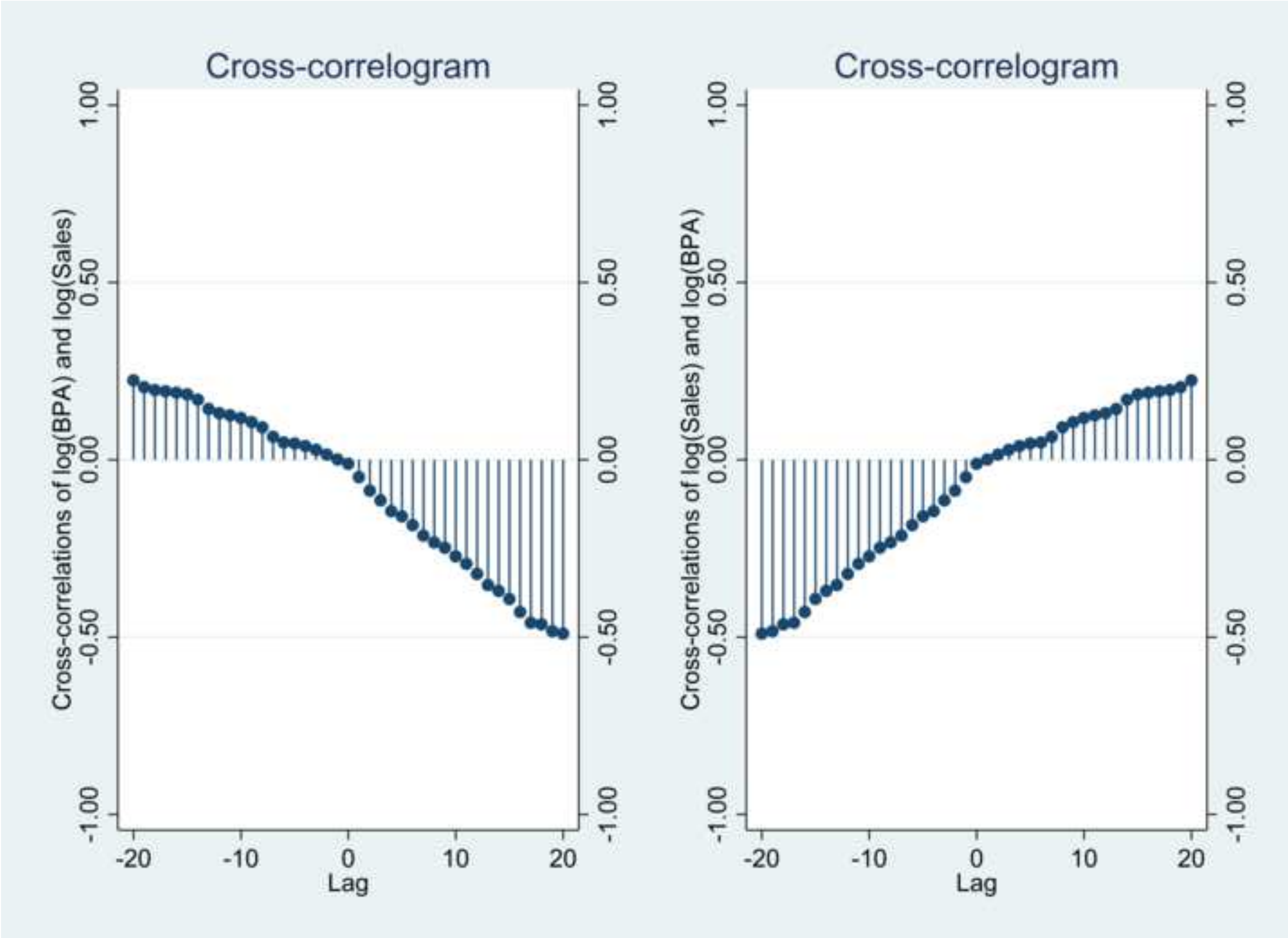


Figure 8



Cross-correlogram
Cross-correlations of log(BPA) and log(Sales)
1.00
0.50
0.00
-0.50
-1.00
-20
-10
0
10
20
Lag
Cross-correlogram
Cross-correlations of log(Sales) and log(BPA)
1.00
0.50
0.00
-0.50
-1.00
-20
-10
0
10
20
Lag

Figure 9

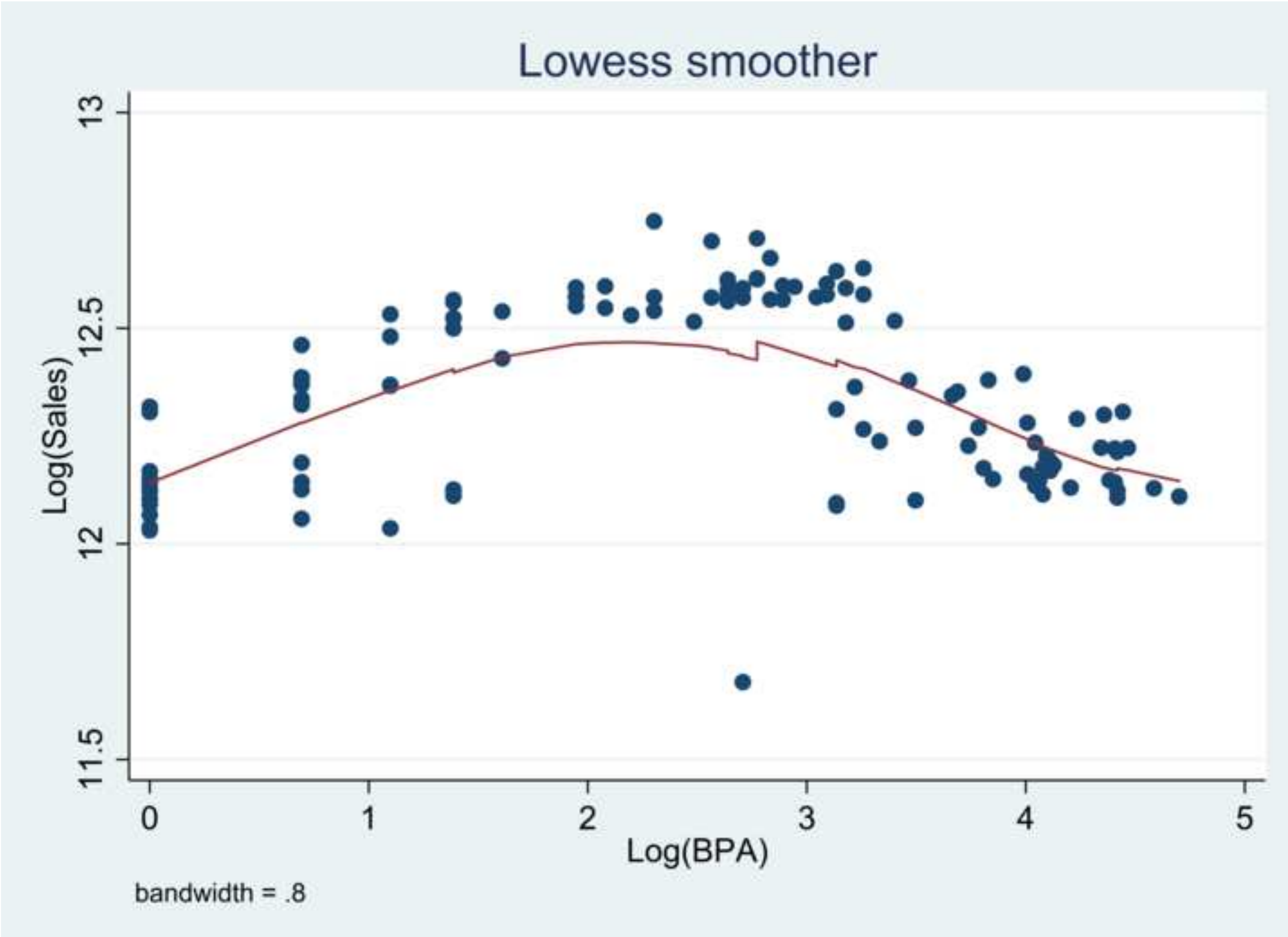

Lowess smoother
Log(Sales)
13
12.5
12
11.5
0
1
2
3
4
5
Log(BPA)
bandwidth = .8

Figure 10

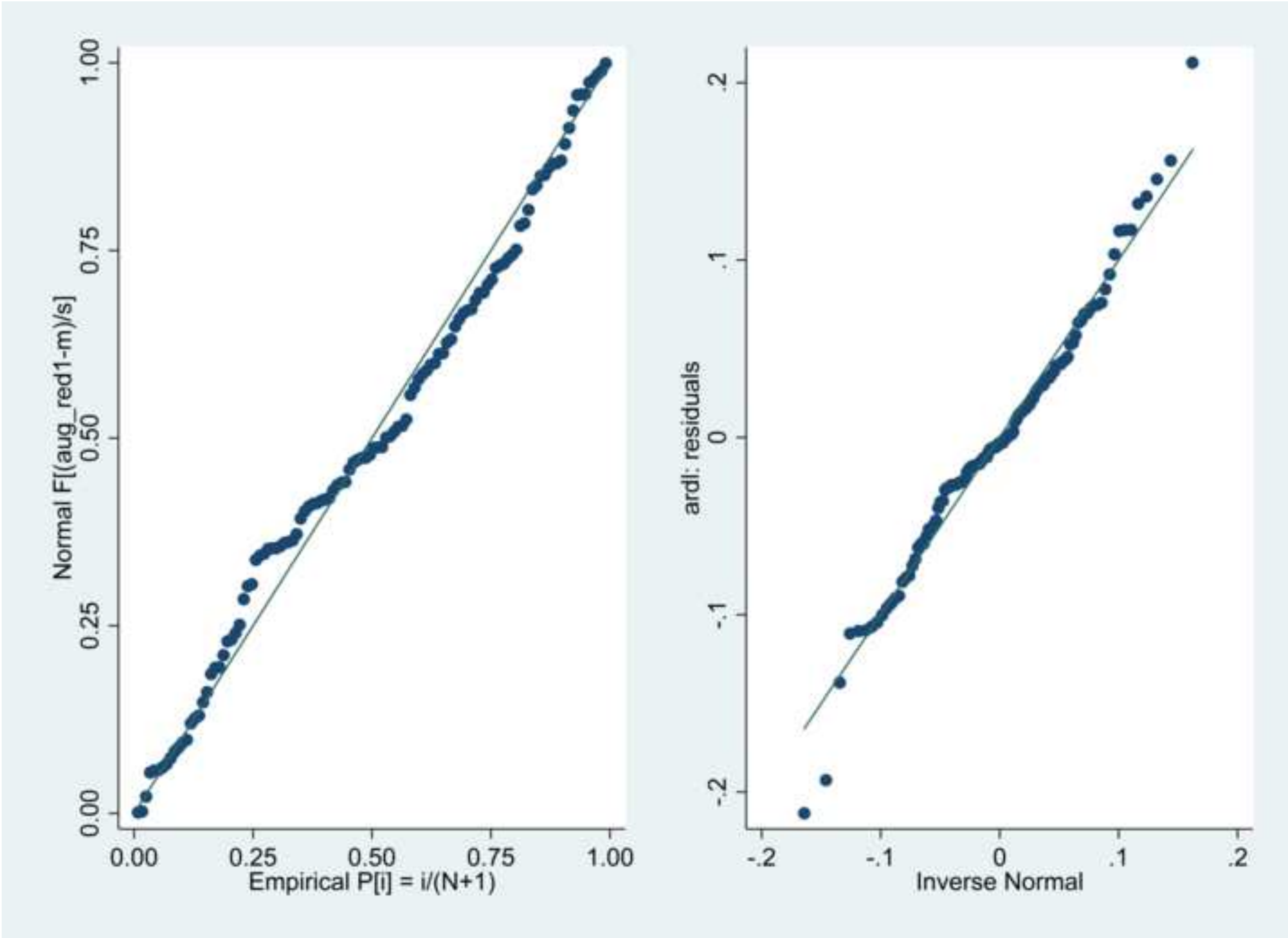

Normal F[(aug_red1-m)/s]
0.00
0.25
0.50
0.75
1.00
Empirical P[i] = i/(N+1)
ardl: residuals
-.2
-.1
0
.1
.2
Inverse Normal

Figure 11 left

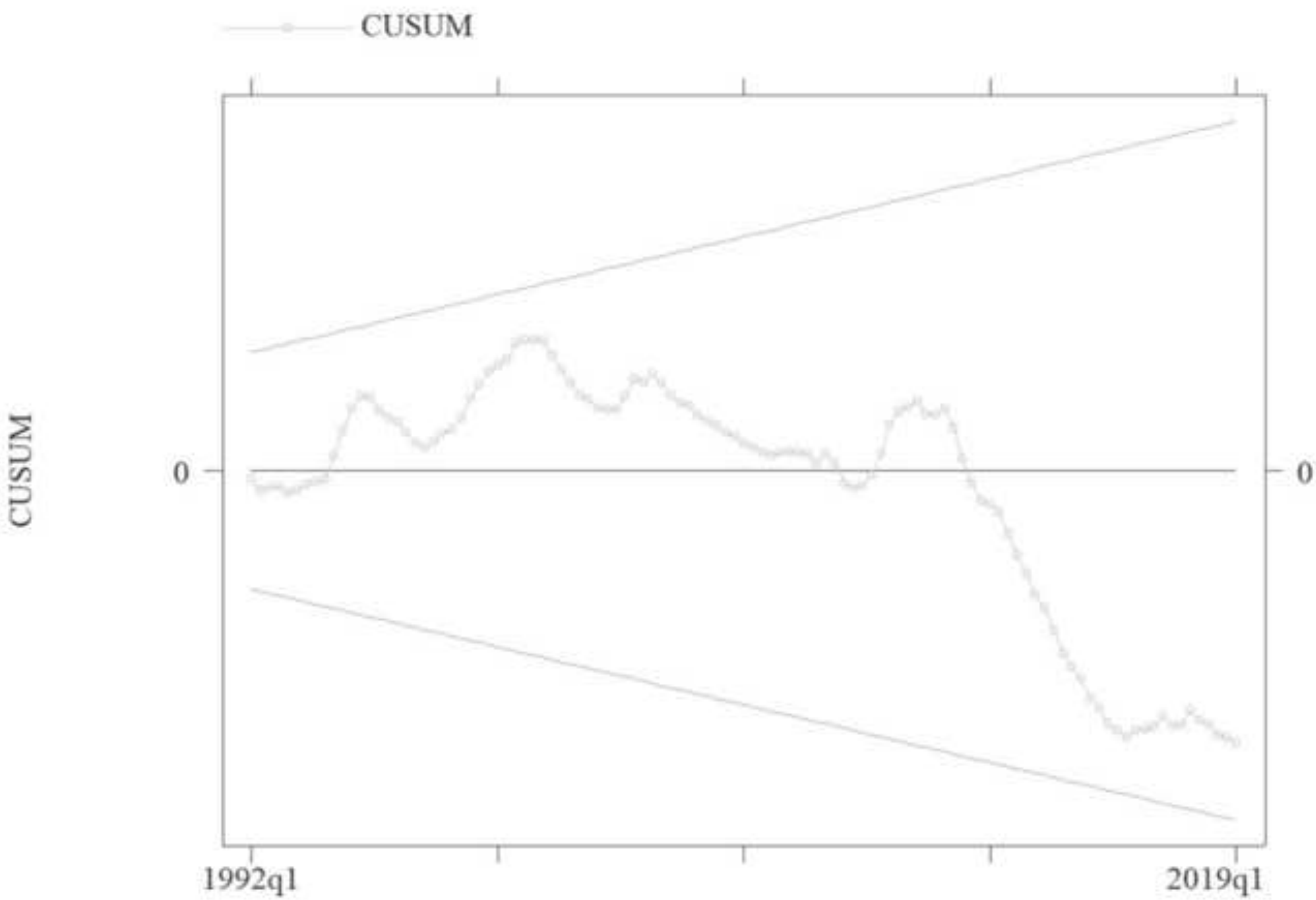


Figure 11 right