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Air Pollution and Perinatal Health: The Protective Role of Public Service Provision

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Abstract

Ambient air pollution is widely recognized as an important determinant of adverse perinatal outcomes, yet the extent to which broader health and social care systems can mitigate these environmental risks remains insufficiently understood. Drawing on a 20-year provincial panel dataset from China, this study examines the association between ambient air pollution and perinatal health, with particular attention to the role of public service provision. Using a panel threshold modelling approach, this study explores potential non-linear buffering effects across both traditional public services and digital infrastructure. The findings indicate that higher levels of air pollution are consistently associated with poorer perinatal health outcomes. Importantly, this association varies systematically with the level of public service provision. In regions with stronger health and social care systems, the adverse association between air pollution and perinatal health is significantly attenuated, suggesting that service capacity plays a protective role in the context of environmental risk. Further analysis indicates that this moderating effect is non-linear, with the buffering function of public services becoming substantially more pronounced once a certain level of provision is reached. These results highlight that perinatal health is shaped not only by environmental exposure, but also by the capacity of health and social care systems to respond to such risks. Strengthening public service provision, alongside efforts to reduce digital inequalities, may therefore represent important pathways for improving maternal and neonatal health and reducing environmentally related health disparities.

1. Introduction

1.1 Air pollution and perinatal health

Ambient air pollution remains a major global public health concern and an important driver of environmental health inequalities. According to recent estimates, a large proportion of the world's population lives in areas where air quality does not meet the fine particulate matter (PM2.5) guidelines set by the World Health Organization, making it a leading environmental risk factor for both morbidity and premature mortality (WHO, 2023). Although deteriorating air quality affects populations broadly, its impacts are not evenly distributed (Fan et al., 2023). Instead, certain groups bear a disproportionate burden, particularly pregnant women and developing fetuses (Arceo et al., 2016). Within this context, the perinatal period, which spans late pregnancy and the early neonatal stage, represents a particularly sensitive developmental window during which environmental exposures may have lasting consequences (Ghosh et al., 2021). A growing body of research has consistently shown that maternal exposure to ambient air pollutants during pregnancy is associated with a range of adverse birth outcomes. In particular, exposure to fine particulate matter has been linked to increased risks of preterm birth, low birth weight, intrauterine growth restriction, and early neonatal mortality (Liu et al., 2020; Xu et al., 2024). The underlying physiological mechanisms are increasingly well understood. For example, inhalation of PM2.5 may induce systemic oxidative stress, inflammatory responses, and endothelial dysfunction within the maternal circulatory system, thereby affecting fetal development (Vardoulakis et al., 2020). Among the available indicators of maternal and child health, perinatal mortality is widely regarded as a

comprehensive and sensitive measure. It reflects not only biological vulnerability during fetal development but also the broader performance of healthcare and social support systems (UNICEF, 2021). For this reason, it provides a useful lens through which to examine the combined influence of environmental and social factors on health outcomes.

While biological mechanisms provide important insights into how air pollution affects health, they offer only a partial explanation of the overall process. From the perspective of community health and social care, the relationship between environmental exposure and perinatal health is more fully understood when placed within a broader social and structural context. The health effects of environmental hazards are not determined solely by levels of exposure; they are also shaped by the Social Determinants of Health (SDOH) and by the capacity of communities to respond to and manage these risks (Marmot, 2020). Research on environmental justice suggests that socioeconomic disadvantage often coincides with higher exposure to environmental risks and more limited access to protective resources. Populations in lower socioeconomic positions are more likely to live in more polluted areas, while also facing constraints in accessing healthcare, adequate nutrition, and social support (Arceo et al., 2016; Fan et al., 2023). As a result, vulnerability in this context extends beyond biological sensitivity to include unequal access to structural resources that influence how individuals and communities cope with environmental stressors.

1.2 Public service provision as a protective system in maternal and child health

Within this broader framework, public service provision can be understood as a key structural mechanism through which environmental risks may be mitigated. Public services encompass a wide range of interventions at both the state and community levels, including healthcare infrastructure, maternal and child health programmes, environmental monitoring systems, and social care support (Wang et al., 2024). Together, these services form an institutional safety net that plays an important role in protecting vulnerable populations. For pregnant women living in areas with high levels of air pollution, access to effective public services may significantly influence health outcomes. Timely prenatal care, continuous maternal health monitoring, and access to emergency obstetric services can help reduce the potential harm associated with environmental exposure. Evidence from previous studies suggests that improvements in maternal healthcare coverage are often accompanied by reductions in neonatal and perinatal mortality, even in settings where environmental risks persist (Kruk et al., 2018).

To better understand this protective role, it is useful to consider several key components of public service provision. Medical and health services represent the most direct form of intervention, enabling early identification and management of pregnancy-related risks associated with environmental exposure (Zhong et al., 2024). At the same time, public education contributes to prevention by improving population-level health literacy. Higher levels of education are generally associated with a greater ability to understand health information, interpret air quality indicators, and adopt protective behaviors (Baker et al., 2017; Balaj et al., 2024; Finn & O'Fallon, 2017). In addition, environmental protection services

contribute by reducing exposure risks and enhancing community-level resilience, for example through monitoring systems and early warning mechanisms (Fan et al., 2022; Han et al., 2022; Qian et al., 2023).

Alongside these traditional components, ongoing digital transformation has introduced new dimensions to the delivery of health and social care. Digital infrastructure, including internet access, online health platforms, and information systems, is increasingly recognized as an important component of public health capacity (Schulte & Hudson, 2023; Zhong et al., 2024). In recent years, this development has also been discussed in terms of the "Digital Determinants of Health" (DDoH), which highlights how access to and effective use of digital technologies can shape health opportunities and outcomes (Kickbusch et al., 2021). From this perspective, digital tools can play a meaningful role in reducing barriers to healthcare access. For example, telemedicine and remote consultation services allow pregnant women to obtain timely medical advice without unnecessary exposure to polluted environments (DeNicola et al., 2020). In addition, digital platforms provide access to real-time environmental information, enabling individuals to make more informed decisions regarding their daily exposure. At the same time, the expansion of digital services also raises concerns about unequal access. The persistence of the digital divide means that some groups, particularly those in rural or socioeconomically disadvantaged areas, may not benefit equally from these developments (Crawford & Serhal, 2020; Liu et al., 2024). In such contexts, digitalization may inadvertently reinforce existing inequalities if access to these services remains uneven (Sieck et al., 2021). Understanding how digital and traditional forms of service provision jointly shape health outcomes is therefore an important area of inquiry.

1.3 Research gaps and the present study

Despite growing recognition of the interconnected roles of environmental, biological, and social factors in shaping health outcomes, several important gaps remain in the existing literature. Much of the current research has focused on estimating the direct effects of air pollution on health, often assuming a relatively simple and linear relationship. In comparison, less attention has been given to how broader social and service-related contexts may influence or condition these effects. In particular, the potential for public service systems to act as protective mechanisms in the context of environmental exposure has not been fully examined. In addition, existing studies tend to treat public service provision as having uniform effects across different contexts. However, in practice, the capacity of health and social care systems is likely to evolve in stages. Incremental increases in resources may not immediately translate into meaningful improvements in outcomes, especially when systems operate below a certain level of functionality. It is therefore plausible that the protective role of public services becomes more evident only after reaching a critical level of development, at which point their capacity to buffer environmental risks is substantially enhanced. However, empirical evidence on such non-linear dynamics remains limited, especially in the context of maternal and child health.

To address these issues, the present study draws on a 20-year provincial panel dataset from China (2003–2022) to examine the relationship between ambient air pollution and perinatal health. Rather than focusing solely on direct effects, the analysis considers how this relationship may vary across different levels of public service provision, including both traditional services and emerging digital capacities. By

adopting a panel threshold modelling approach, the study is able to capture potential non-linearities in these relationships and to identify whether there are specific levels of service provision at which protective effects become more pronounced. In doing so, this study brings together perspectives from environmental health and social care, offering a more integrated account of how structural conditions shape health outcomes under environmental risk. It also provides empirical evidence on how different dimensions of public service provision, including healthcare, education, environmental protection, and digital access, may operate jointly to mitigate adverse effects on perinatal health. These considerations lead to the following hypotheses:

Hypothesis 1

Ambient air pollution is negatively associated with perinatal health, increasing the risk of adverse outcomes.

Hypothesis 2

Public service provision plays a buffering role, such that the negative association between air pollution and perinatal health is weaker in regions with higher levels of service capacity.

Hypothesis 3

The buffering effect of public services is non-linear, with stronger protective effects emerging once service provision reaches certain threshold levels.

2. Methods

2.1 Data

This study is based on a balanced panel dataset covering 31 provinces in China over the period from 2003 to 2022. Data on ambient air pollution are obtained from the Atmospheric Composition Analysis Group at Washington University, which provides both population-weighted and geographic-mean PM2.5 concentrations estimated using aerosol optical depth (AOD) in combination with the GEOS-Chem chemical transport model. These data have been widely used in studies examining population exposure to air pollution (Luo et al., 2017; Wang et al., 2019). Information on perinatal health and socioeconomic characteristics is collected from the China Health and Family Planning Statistical Yearbook, the China Statistical Yearbook, and provincial statistical yearbooks. Missing observations are addressed using linear interpolation. To reduce potential heteroscedasticity, selected variables are transformed using natural logarithms.

2.2 Measures

2.2.1 Perinatal health

The main outcome variable is perinatal health (*Health*). Consistent with the study's focus on maternal and neonatal outcomes, perinatal health is measured using the inverse of the perinatal mortality rate. This indicator captures health conditions during a critical stage of life and is particularly suitable for assessing the health consequences of environmental exposure, as infants are more sensitive to air pollution compared with the general population (Luechinger, 2014; Maisonet et al., 2001).

2.2.2 Air pollution exposure

Ambient air pollution (*Air*). PM10 and PM2.5 have the most serious effects on human health (Almetwally et al., 2020), which have a higher risk of retention in the atmosphere than other types of atmospheric pollutants. Moreover, compared with PM10, PM2.5 can even penetrate the lung barrier into the bloodstream, and prolonged exposure may elevate the risk of respiratory diseases and lung cancer (Almetwally et al., 2020; Gautam & Bolia, 2020), therefore, PM2.5 concentration is more appropriate as a measure of air pollution. In general, there are two primary ways for estimating regional PM2.5 concentrations: population-weighted and geographic-mean. The population-weighted PM2.5 concentration, measured on the basis of spatial distribution of overall exposure, is considered better for assessing the health impacts of air pollution on infants and children (Liu et al., 2020). Therefore, this study uses the population-weighted annual average PM2.5 concentrations as the proxy variables of regional ambient air pollution. Additionally, geographic-mean PM2.5 concentrations are used to test the robustness of this study.

2.2.3 Public service provision

To examine the role of public service systems in shaping health outcomes, this study conceptualized public service provision as a multidimensional construct, including both traditional public services and digital public services.

Traditional public services are captured using fiscal expenditure indicators. Medical and health services (*Med*) are measured by healthcare expenditure of local finance, environmental protection services (*Env*) by environmental protection expenditure of local finance, and public education services (*Edu*) by educational expenditure of local finance. These indicators reflect the level of government investment in key service domains that are closely related to population health (Fan et al., 2023).

In addition, digital public services are measured from three aspects. Internet infrastructure (*Int-inf*) is proxied by the provincial IPv4 address proportion, Internet applications (*Int-app*) by the average number of domain names per 10,000 people, and Internet information resources (*Int-res*) by the average web page byte count (Byaro et al., 2023). These indicators respectively capture infrastructure capacity, service utilization, and information availability, thereby reflecting the broader digital environment that may support health risk management (Wu et al., 2022; Yang et al., 2021).

2.2.4 Control variables

Based on previous studies, a range of control variables is included to account for other factors that may influence perinatal health outcomes (Balaj et al., 2024; Cao et al., 2024; Chen et al., 2017; Qin et al., 2023;

Wang et al., 2022). Economic development (*PGDP*) is measured by per capita GDP. Social and demographic characteristics are captured by population density (*PD*), urbanization level (*URB*), and technological capacity (*RD*), measured respectively by population per unit area, the proportion of urban population, and the full-time equivalent number of R&D personnel. Educational attainment (*Aedu*) is measured by average years of schooling, while healthcare resources (*Pmedsp*) are proxied by per capita healthcare expenditure.

2.3 Analytical strategy

This study adopts a two-step empirical strategy. First, inspired by Grossman's health production function (Grossman, 1972), a two-way fixed effects model is used to examine the association between ambient air pollution and perinatal health, controlling for both province-specific and time-specific unobserved heterogeneity (Cropper, 1981).

Second, to assess whether the relationship between air pollution and perinatal health varies across different levels of public service provision, a panel threshold model is employed. This approach allows the effect of air pollution on perinatal health to change when public service provision crosses certain threshold levels, thereby capturing potential non-linearities in the protective role of service systems (Hansen, 1999; Shao & Shen, 2017; Wang et al., 2024). In this framework, indicators of public service provision are introduced as threshold variables, enabling the identification of stage-specific differences in how environmental risks translate into health outcomes. All analyses are conducted using Stata 17.0.

3. Results

3.1 Descriptive statistics

The descriptive statistics of main variables are presented in Table 1. Overall, substantial variation is observed across provinces in both perinatal health outcomes and levels of air pollution. Such variation provides an important empirical basis for examining how air pollution and public service provision jointly shape perinatal health outcomes across different contexts.

Table 1
Descriptive statistics.

Variable	Explanation	Mean	Std	Min	Max
Health	Inverse of perinatal mortality rate	0.175	0.089	0.039	0.556
lnAir	Logarithm of population-weighted PM2.5 concentration	3.705	0.466	1.872	4.488
lnPGDP	Logarithm of GDP per capita	10.405	0.755	8.719	11.963
lnPD	Logarithm of population density	7.729	0.599	5.442	8.679
lnSexra	Logarithm of the sex ratio of the population	4.647	0.035	4.560	4.748
lnURB	Logarithm of urbanization level	-0.653	0.292	-1.501	-0.113
lnRD	Logarithm of full-time equivalent number of R&D personnel	10.101	1.738	3.664	13.326
lnAedu	Logarithm of average schooling years	2.159	0.152	1.515	2.517
lnPmedsp	Logarithm of per capita healthcare expenditure	-3.069	1.127	-5.817	-1.215

3.2 The effects of air pollution on perinatal health

The baseline regression results are reported in Table 2. Based on the Hausman test, a two-way fixed effects model is adopted to control for both province-specific and time-specific unobserved heterogeneity. The results indicate that ambient air pollution is significantly associated with poorer perinatal health outcomes. Specifically, the coefficient of *lnAir* is − 0.071 ($p < 0.01$), suggesting that a one-unit increase in air pollution is associated with a 0.071-unit decrease in perinatal health. Given that the dependent variable is constructed as the inverse of perinatal mortality, this finding implies that higher pollution levels are linked to increased risks of adverse birth outcomes, including stillbirth and early neonatal death.

This association remains robust across alternative model specifications. When provincial average PM2.5 concentration is used as an alternative measure of air pollution, the estimated coefficient remains negative and statistically significant ($\beta = -0.087$, $p < 0.01$). In addition, when the one-period lagged value of air pollution is introduced to address potential endogeneity, the coefficient remains significant ($\beta = -0.053$, $p < 0.01$). The consistency of these findings across different specifications provides strong support for Hypothesis 1, indicating a stable and negative relationship between air pollution and perinatal health.

Table 2
Baseline regression and robustness test results.

lnAir	**Model 1**	**Model 2**	**Model 3**
	-0.071* **	**-0.087*** **	**-0.053*** **
(0.013)	**(0.013)**	**(0.014)**	
lnPGDP	-0.003	-0.004	-0.012
	(0.017)	(0.017)	(0.018)
lnPD	-0.012***	-0.013***	-0.012***
	(0.003)	(0.003)	(0.004)
lnSexra	-0.141***	-0.137***	-0.121**
	(0.048)	(0.048)	(0.048)
lnURB	-0.005	-0.003	-0.019
	(0.026)	(0.027)	(0.028)
lnRD	0.010**	0.010**	0.010**
	(0.004)	(0.004)	(0.004)
lnAedu	-0.069	-0.071	-0.050
	(0.049)	(0.049)	(0.052)
lnPmedsp	0.024***	0.025***	0.033***
	(0.008)	(0.008)	(0.008)
Constant	1.407***	1.363***	1.313***
	(2.931)	(0.283)	(0.292)
Year dummy	YES	YES	YES
Province dummy	YES	YES	YES
N	620	620	589
R^2	0.905	0.904	0.907

Note: Standard errors are presented in parentheses, and significance levels are indicated as follows: * p < 0.1, ** p < 0.05, *** p < 0.01. The same is true below.

3.3 Threshold effects of public service provision

To further examine whether public service provision conditions the relationship between air pollution and perinatal health, threshold effect models are estimated. The results of the threshold effect tests are presented in Table 3. The findings show that several dimensions of public service provision exhibit statistically significant threshold effects. In particular, medical and health services and environmental protection services demonstrate double-threshold effects at the 5% significance level, while public education and the three dimensions of internet-based services display single-threshold effects. These results suggest that the association between air pollution and perinatal health varies across different levels of service provision, rather than remaining constant.

Table 3
Tests for the existence of threshold effects.

Threshold variables	Number of thresholds	F-value	p-value	Critical values		
				10%	5%	1%
Medical and health	Single	70.79***	< 0.001	26.08	33.91	57.61
	Double	31.31***	0.02	19.40	21.73	45.12
	Triple	7.97	0.77	29.58	33.55	37.54
Environmental protection	Single	68.38***	< 0.001	27.25	33.43	49.52
	Double	26.08***	0.03	18.93	21.07	28.01
	Triple	7.92	0.71	27.97	33.28	52.55
Public education	Single	88.88	< 0.001	31.97	41.24	57.98
	Double	22.54	0.19	25.16	32.05	51.25
Internet infrastructure	Single	37.19**	0.04	28.62	31.53	46.09
	Double	27.49	0.13	29.56	34.46	51.84
Internet applications	Single	26.63**	0.04	21.98	24.67	29.44
	Double	14.60	0.10	14.44	20.50	31.24
Internet information resources	Single	27.53**	0.03	23.78	25.54	33.87
	Double	4.33	0.88	23.03	32.13	52.81

The estimated threshold values and their corresponding confidence intervals are reported in Table 4. For instance, the thresholds for medical and health services are identified at 198.05 and 434.45, while those for environmental protection services are 95.26 and 176.02. The likelihood ratio (LR) functions presented

in Figs. 1 and 2 further support the validity of these threshold estimates, as all LR statistics fall below the critical value at the 95% confidence level. This indicates that the identified thresholds are statistically robust and provide a reliable basis for subsequent analysis.

Table 4
Threshold estimation results and confidence intervals.

Threshold variables	Threshold	Estimated value	95% confidence interval
Medical and health	First	198.05***	(184.14, 202.32)
	Second	434.45**	(422.72, 455.31)
Environmental protection	First	95.26***	(87.27, 95.86)
	Second	176.02**	(167.41, 181.88)
Public education	First	837.63***	(792.79, 888.58)
Internet infrastructure	First	0.016***	(0.014, 0.017)
Internet applications	First	524.37***	(467.39, 596.30)
Internet information resources	First	76.30***	(72.48, 83.00)

3.4 The buffering role of traditional public services

The regression results of the panel threshold models with traditional public services are reported in Table 5. A clear pattern emerges across different specifications: as the level of public service provision increases, the negative association between air pollution and perinatal health becomes progressively weaker.

Table 5
Regression results with traditional public services as threshold variables.

Coefficients	***Medical and health*** **(Med) as Threshold Variable**	***Environmental protection*** **(Env) as Threshold Variable**	***Public education*** **(Edu) as Threshold Variable**
lnAir (Med ≤ 198.05)	-0.065***		
	(0.018)		
lnAir (198.05 < Med ≤ 434.45)	-0.060***		
	(0.018)		
lnAir (434.45 < Med)	-0.051***		
	(0.018)		
lnAir (Env ≤ 95.26)		-0.064***	
		(0.017)	
lnAir (95.26 < Env ≤ 176.02)		-0.059***	
		(0.017)	
lnAir (176.02 < Env)		-0.051***	
		(0.017)	
lnAir (Edu ≤ 837.63)			-0.063***
			(0.017)
lnAir (837.63 < Edu)			-0.053***
			(0.018)
Constant	0.758	0.912*	0.984*
	(0.488)	(0.499)	(0.506)
Control Variables	YES	YES	YES
Year dummy	YES	YES	YES
Province dummy	YES	YES	YES
N	620	620	620
R^2	0.202	0.254	0.171

Taking medical and health services as an example, when service provision is below the first threshold (Med ≤ 198.05), the coefficient of air pollution is − 0.065 ($p < 0.01$). When service provision lies between the first and second thresholds (198.05 < Med ≤ 434.45), the magnitude of the coefficient decreases slightly to − 0.060 ($p < 0.01$). Once service provision exceeds the second threshold (Med > 434.45), the coefficient further attenuates to − 0.051 ($p < 0.01$). This gradual reduction in effect size indicates that stronger healthcare systems can partially offset the adverse effects of environmental exposure on perinatal outcomes.

A similar pattern is observed for environmental protection and public education services. For environmental protection, the coefficient of air pollution decreases from − 0.064 to − 0.051 as expenditure levels cross the identified thresholds. For public education, the coefficient declines from − 0.063 to − 0.053 after exceeding the threshold. These findings suggest that broader social service systems, beyond direct healthcare provision, also play an important role in mitigating environmental health risks. Improvements in these areas may enhance population-level resilience by improving living conditions, increasing awareness, and strengthening preventive capacities.

3.5 The buffering role of digital public services

The moderating role of digital forms of public service provision is presented in Table 6. The results show that improvements in internet infrastructure, applications, and information resources are associated with a significant attenuation of the negative effects of air pollution on perinatal health.

Table 6
Regression results with Internet public services as threshold variables.

Coefficients	***Internet infrastructure*** **as Threshold Variable**	***Internet applications*** **as Threshold Variable**	***Internet information resources*** **as Threshold Variable**
lnAir (ln_inf ≤ 0.016)	-0.090***		
	(0.018)		
lnAir (0.016<ln_inf)	-0.080***		
	(0.017)		
lnAir (ln_app ≤ 524.37)		-0.082***	
		(0.018)	
lnAir (524.37 < ln_app)		-0.072***	
		(0.017)	
lnAir (ln_res ≤ 76.30)			-0.075***
			(0.017)
lnAir (76.30 < ln_res)			-0.066***
			(0.018)
Constant	0.922	1.024*	0.820
	(0.556)	(0.578)	(0.574)
Control Variables	YES	YES	YES
Year dummy	YES	YES	YES
Province dummy	YES	YES	YES
N	620	620	620
R^2	0.199	0.187	0.223

Specifically, when internet infrastructure exceeds the threshold value of 0.016, the coefficient of air pollution decreases from − 0.090 to − 0.080 ($p < 0.01$). For internet applications, when the average number of domain names per 10,000 persons exceeds 524.37, the coefficient declines from − 0.082 to − 0.072 ($p < 0.01$). Similarly, for internet information resources, when the average web page volume exceeds 76.30, the coefficient decreases from − 0.075 to − 0.066 ($p < 0.01$). These results indicate that digital service capacity may enhance access to health information, facilitate service utilization, and improve individuals' ability to respond to environmental risks.

Taken together, these findings suggest that both traditional and digital forms of public service provision play a significant buffering role in the relationship between air pollution and perinatal health. Importantly, this moderating effect is characterized by clear non-linear dynamics, with the protective function of public services becoming more pronounced once a certain level of provision is reached. These results provide consistent support for Hypotheses 2 and 3 and highlight the importance of strengthening service systems as part of broader strategies to reduce environmental health inequalities.

4. Discussion

The primary aim of this study was to examine the association between ambient air pollution and perinatal health, with particular attention to the non-linear moderating roles of both traditional and digital public service provision in buffering environmental health risks. Drawing on a 20-year longitudinal panel dataset from China, the findings indicate that exposure to PM2.5 constitutes a significant structural risk for perinatal populations. At the same time, the results suggest that the extent of this risk is closely shaped by the strength and accessibility of regional health and social care systems. The threshold analyses further indicate that public service provisions do not exert linear additive effects. Rather, they function as critical social buffers that significantly attenuate environmental harm once specific developmental thresholds are surpassed. These findings provide compelling empirical support for the integration of environmental health strategies with community-based social care enhancements, shifting the narrative from passive pollution exposure to active community resilience.

4.1 The Negative Effect of Air Pollution on Perinatal Health

The baseline results demonstrate a consistent negative effect of ambient air pollution on perinatal health. Specifically, higher population-weighted PM2.5 concentrations were consistently linked to poorer perinatal health outcomes, as reflected by the reduction in the inverse perinatal mortality rate.

This finding aligns with a substantial body of epidemiological research indicating that fetuses and newborns are particularly sensitive to environmental exposures due to physiological immaturity, higher respiratory rates relative to body weight, and developing immune systems (Ghosh et al., 2021; Liu et al., 2020; Xu et al., 2024). From a biological perspective, maternal exposure to PM2.5 may trigger a range of adverse responses, including oxidative stress, inflammation, and endothelial dysfunction, which can compromise placental function and elevate the risk of stillbirth and early neonatal death (Vardoulakis et al., 2020). However, within a health and social care framework, these mechanisms are more appropriately understood as operating within broader social contexts. The effects of air pollution are not solely toxicological; they are also shaped by underlying social and structural conditions. This perspective is supported by empirical evidence, as demonstrated by Arceo et al. (2016), who show that the impact of pollution on infant mortality differs significantly between developing and developed countries. In many cases, populations exposed to higher levels of air pollution also face socioeconomic disadvantage, which may limit access to protective resources such as cleaner indoor environments, adequate nutrition, or the ability to relocate (Fan et al., 2023; Marmot, 2020). In this sense, ambient air pollution can be

understood as an external stressor that interacts with existing vulnerabilities. This perspective highlights that addressing air pollution is closely linked to broader concerns of health equity, and that the role of public service systems is particularly important in mitigating these compounded risks.

4.2 Buffering effects of medical and health services

A key finding of this study is the presence of a double-threshold moderating effect of medical and health service provision. The results indicate that the negative association between air pollution and perinatal health becomes progressively weaker as healthcare expenditure surpasses successive threshold levels. This pattern provides insight into how healthcare systems may function as protective structures in the context of environmental risk.

This finding can be interpreted in relation to the Inverse Care Law proposed by Tudor Hart, which suggests that the availability of high-quality care often varies inversely with population need (Cookson et al., 2021; Hart, 1971). In regions below the first threshold, healthcare systems may lack the capacity to effectively identify and manage high-risk pregnancies associated with environmental exposure (Kruk et al., 2018). For example, limited diagnostic capabilities may constrain the early detection of conditions such as preeclampsia or intrauterine growth restriction, allowing the effects of pollution exposure to translate more directly into adverse outcomes (Nair et al., 2015). However, as healthcare investments cross higher thresholds, the health system transitions from providing basic, reactive care to comprehensive, preventative, and specialized social care (Wang et al., 2024). This likely reflects improvements not only in resource availability but also in service quality and coordination (Gallegos et al., 2023). Enhanced prenatal screening, better-trained medical personnel, and expanded neonatal care capacity may all contribute to earlier intervention and improved outcomes. In this context, the observed attenuation of the pollution effect can be understood as reflecting the growing ability of the healthcare system to manage and mitigate environmentally induced risks.

4.3 Buffering effects of public education and environmental protection services

In addition to medical and health services, the study identifies significant moderating roles for public education and environmental protection services. Once these services reach certain levels, the adverse effects of air pollution on perinatal health are noticeably reduced.

This finding can be explained through Link and Phelan’s Fundamental Cause Theory, which argues that socioeconomic resources, including education, are fundamental causes of health inequalities because they determine an individual’s access to flexible resources that can be used to avoid risks or minimize the consequences of disease (Link & Phelan, 1995; Phelan et al., 2010). In the context of perinatal environmental health, public education acts as a proxy for community-level environmental health literacy (Finn & O’Fallon, 2017). Higher regional educational provision means that expectant mothers and their families are more capable of comprehending complex health risks associated with PM2.5 (Baker et al., 2017; Balaj et al., 2024). They are more likely to understand Air Quality Index (AQI) alerts, modify their

behavior by staying indoors on heavily polluted days, adhere strictly to prenatal supplement regimens, and advocate for themselves within the medical system (Pleasant et al., 2015). Consequently, robust public education transforms passive populations into proactive health agents, structurally reducing their functional exposure to ambient pollution.

Similarly, the threshold effect of environmental protection services reflects the transition of local governance from passive regulation to active preventive social care. High levels of environmental expenditure do not only mean stricter factory regulations but also can be transformed into community resilience features (Fan et al., 2022), such as deploying real-time community-level air quality monitoring networks and creating urban green spaces that act as absorbers of particulate matter (Fu et al., 2024; Han et al., 2022; Qian et al., 2023). These structural investments create a protective environmental envelope around vulnerable populations, proving that ecological governance is intrinsically linked to community social care.

4.4 Digital determinants of health and the buffering effects of digital public services

An additional contribution of this study lies in identifying the moderating role of digital public services. The results indicate that improvements in internet infrastructure, digital applications, and information resources are associated with a reduced impact of air pollution on perinatal health, particularly after certain thresholds are reached.

These findings align with the emerging public health paradigm of the Digital Determinants of Health (DDoH) (Kickbusch et al., 2021). In the digital age, internet access has become a key means to achieve health equity (Sieck et al., 2021). Access to digital technologies can facilitate the dissemination of health information, improve communication between patients and providers, and support more flexible forms of care delivery (Schulte & Hudson, 2023; Zhong et al., 2024). For pregnant women, this may include access to real-time air quality information, telemedicine consultations, and online health resources (DeNicola et al., 2020). The observed threshold effects suggest that the benefits of digital services depend not only on access but also on effective use. In regions with limited digital infrastructure, individuals may be excluded from these forms of support (Crawford & Serhal, 2020; Liu et al., 2024). In contrast, once a certain level of digital development is achieved, digital tools may become integrated into routine health management, thereby enhancing individuals' ability to respond to environmental risks (Byaro et al., 2023). These findings highlight the importance of addressing digital inequalities as part of broader health and social care strategies. Digital inclusion may play a meaningful role in reducing disparities in exposure and access to care, particularly in the context of environmental health challenges.

5. Implications

The findings of this study have important and practical implications for policymakers, community health practitioners, and social workers, highlighting the need to more closely integrate environmental health considerations into everyday health and social care practice.

First, there is a need to adopt a “Health in All Policies” approach at the macro-policy level. The finding that the health effects of air pollution are strongly conditioned by the level of public service provision suggests that environmental mitigation strategies, such as emission controls, may be insufficient on their own, particularly for more vulnerable populations. To be effective, these strategies need to be accompanied by sustained investment in local health and social care systems. This also points to the importance of moving beyond fragmented, sector-specific policy approaches. The threshold levels identified in this study may provide a useful reference for resource allocation, indicating where additional investment is likely to yield meaningful health benefits. In particular, regions that remain below key thresholds in healthcare and education may require targeted financial support and capacity-building efforts to strengthen their ability to respond to environmental health risks.

Second, the findings suggest the value of further integrating environmental risk considerations into community-based care. Community nurses and social workers are often in close contact with pregnant women and may therefore play a key role in identifying and addressing environmental health risks. Incorporating basic environmental risk assessment into routine perinatal care could help to improve early awareness and prevention. In practice, this may involve updating maternal health guidance to include advice on reducing exposure during periods of high pollution. At the community level, digital tools could be used to provide timely air quality alerts, behavioral guidance, and health information to pregnant women in higher-risk areas. In addition, social workers may play an important role in supporting low-income families in accessing relevant resources, such as subsidies for indoor air quality improvement. Recognizing the importance of a safe and healthy environment for maternal and infant wellbeing may help to broaden the scope of social care practice in a meaningful and context-sensitive way.

Third, the results highlight the importance of addressing digital inequalities as part of health and social care strategies. The findings on digital public services suggest that access to digital infrastructure can play a meaningful role in reducing the health impacts of environmental risk. Ensuring access to affordable and reliable internet services in socioeconomically disadvantaged areas is therefore an important policy priority. At the same time, access alone may not be sufficient. Supporting the development of digital health literacy among vulnerable groups is equally important, so that available tools and services can be effectively used. In this regard, social care organizations have a role to play in designing and delivering digital health services that are accessible and inclusive, taking into account differences in language, education, and familiarity with technology. Such efforts may help to ensure that pregnant women are better able to access and benefit from emerging forms of remote and digital care.

6. Limitations and future directions

Several limitations should be considered when interpreting these findings. First, the use of provincial-level data in China allows for the analysis of broad systemic patterns but may obscure important within-region variation. Future research could make use of more disaggregated data to better capture local differences. Second, although the study employs longitudinal data and lagged models, the possibility of

unobserved confounding cannot be fully ruled out. Further research using alternative methodological approaches may help to strengthen causal inference. Finally, the outcome measure focuses on perinatal mortality and does not capture other important dimensions of maternal and infant health, such as morbidity or developmental outcomes. Expanding the range of health indicators would provide a more comprehensive understanding of the effects of environmental exposure.

Abbreviations

PM2.5
Fine particulate matter
SDOH
Social determinants of health
DDoH
Digital Determinants of Health
AOD
Aerosol optical depth
LR
Likelihood ratio
AQI
Air Quality Index.

Declarations

Ethics approval and consent to participate

This study uses publicly available, aggregated secondary data from official statistical yearbooks and publicly accessible databases, including air pollution data provided by the Atmospheric Composition Analysis Group. The data do not contain any individual-level or identifiable personal information. Accordingly, ethical approval was not required in line with institutional and national research guidelines. Informed consent to participate was not required, as the study did not involve human participants or identifiable personal data.

Consent for publication

Not applicable.

Availability of data and materials

The datasets analyzed during the current study are publicly available.

Competing Interests

The authors declare that they have no competing interests.

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Authors' contributions

KX conceptualized the study, performed the statistical analysis, and drafted the manuscript. SX revised the manuscript for important intellectual content. All authors read and approved the final manuscript.

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References

1. Almetwally, A. A., Bin-Jumah, M., & Allam, A. A. (2020). Ambient air pollution and its influence on human health and welfare: An overview. *Environmental Science and Pollution Research, 27*(20), 24815–24830.
2. Arceo, E., Hanna, R., & Oliva, P. (2016). Does the Effect of Pollution on Infant Mortality Differ Between Developing and Developed Countries? Evidence from Mexico City. *The Economic Journal, 126*(591), 257–280.
3. Baker, D. P., Smith, W. C., Muñoz, I. G., Jeon, H., Fu, T., Leon, J., Salinas, D., & Horvatek, R. (2017). The Population Education Transition Curve: Education Gradients Across Population Exposure to New Health Risks. *Demography, 54*(5), 1873–1895.
4. Balaj, M., Henson, C. A., Aronsson, A., Aravkin, A., Beck, K., Degail, C., Donadello, L., Eikemo, K., Friedman, J., Giouleka, A., Gradeci, I., Hay, S. I., Jensen, M. R., Mclaughlin, S. A., Mullany, E. C., O'connell, E. M., Sripada, K., Stonkute, D., Sorensen, R. J. D., … Gakidou, E. (2024). Effects of education on adult mortality: A global systematic review and meta-analysis. *The Lancet Public Health, 9*(3), e155–e165.
5. Byaro, M., Rwezaula, A., & Ngowi, N. (2023). Does internet use and adoption matter for better health outcomes in sub-Saharan African countries? New evidence from panel quantile regression. *Technological Forecasting and Social Change, 191*, 122445.
6. Cao, S., Wu, D., Liu, L., Li, S., & Zhang, S. (2024). Decoding the effect of demographic factors on environmental health based on city-level PM2.5 pollution in China. *Journal of Environmental Management, 349,* 119380.
7. Chen, X., Shao, S., Tian, Z., Xie, Z., & Yin, P. (2017). Impacts of air pollution and its spatial spillover effect on public health based on China's big data sample. *Journal of Cleaner Production, 142,* 915–925.
8. Cookson, R., Doran, T., Asaria, M., Gupta, I., & Mujica, F. P. (2021). The inverse care law re-examined: a global perspective. *The Lancet, 397*(10276), 828-838.

9. Crawford, A., & Serhal, E. (2020). Digital health equity and COVID-19: the innovation curve cannot reinforce the social gradient of health. *Journal of medical Internet research, 22*(6), e19361.
10. Cropper, M. L. (1981). Measuring the Benefits from Reduced Morbidity. *The American Economic Review, 71*(2), 235–240.
11. DeNicola, N., Grossman, D., Marko, K., Sonalkar, S., Tobah, Y. S. B., Ganju, N., ... & Lowery, C. (2020). Telehealth interventions to improve obstetric and gynecologic health outcomes: a systematic review. *Obstetrics & Gynecology, 135*(2), 371-382.
12. Fan, W., Yan, L., Chen, B., Ding, W., & Wang, P. (2022). Environmental governance effects of local environmental protection expenditure in China. *Resources Policy, 77,* 102760.
13. Fan, Z., Li, Y., Wei, J., Chen, G., Wang, R., Xu, R., Liu, T., Lv, Z., Huang, S., Sun, H., & Liu, Y. (2023). Long-term exposure to fine particulate matter and site-specific cancer mortality: A difference-in-differences analysis in Jiangsu province, China. *Environmental Research, 222,* 115405.
14. Finn, S., & O'Fallon, L. (2015). The emergence of environmental health literacy—from its roots to its future potential. *Environmental health perspectives, 125*(4), 495.
15. Fu, J., Fu, H., Zhu, C., Sun, Y., & Cao, H. (2024). Assessing the health risk impacts of urban green spaces on air pollution—Evidence from 31 China's provinces. *Ecological Indicators, 159,* 111725.
16. Gallegos, S., Roseth, B., Cuesta, A., & Sánchez, M. (2023). Increasing the take-up of public health services: An at-scale experiment on digital government. *Journal of Public Economics, 227,* 104975.
17. Gautam, D., & B. Bolia, N. (2020). Air pollution: Impact and interventions. *Air Quality, Atmosphere & Health, 13*(2), 209–223.
18. Ghosh, R., Causey, K., Burkart, K., Wozniak, S., Cohen, A., & Brauer, M. (2021). Ambient and household PM2. 5 pollution and adverse perinatal outcomes: a meta-regression and analysis of attributable global burden for 204 countries and territories. *PLoS medicine, 18*(9), e1003718.
19. Grossman, M. (1972). On the Concept of Health Capital and the Demand for Health. *Journal of Political Economy, 80*(2), 223–255.
20. Han, Y., Lee, J., Haiping, G., Kim, K.-H., Wanxi, P., Bhardwaj, N., Oh, J.-M., & Brown, R. J. C. (2022). Plant-based remediation of air pollution: A review. *Journal of Environmental Management, 301,* 113860.
21. Hansen, B. E. (1999). Threshold effects in non-dynamic panels: Estimation, testing, and inference. *Journal of Econometrics, 93*(2), 345–368.
22. Hart, J. T. (1971). The inverse care law. *The lancet, 297*(7696), 405-412.
23. Kickbusch, I., Piselli, D., Agrawal, A., Balicer, R., Banner, O., Adelhardt, M., ... & Wong, B. L. H. (2021). The Lancet and Financial Times Commission on governing health futures 2030: growing up in a digital world. *The Lancet, 398*(10312), 1727-1776.
24. Knittel, C. R., Miller, D. L., & Sanders, N. J. (2016). Caution, Drivers! Children Present: Traffic, Pollution, and Infant Health. *The Review of Economics and Statistics, 98*(2), 350–366.

25. Kruk, M. E., Gage, A. D., Joseph, N. T., Danaei, G., García-Saisó, S., & Salomon, J. A. (2018). Mortality due to low-quality health systems in the universal health coverage era: A systematic analysis of amenable deaths in 137 countries. *The Lancet, 392*(10160), 2203–2212.
26. Link, B. G., & Phelan, J. (1995). Social conditions as fundamental causes of disease. *Journal of health and social behavior,* 80-94.
27. Liu, S., Wei, Q., Failler, P., & Lan, H. (2020). Fine Particulate Air Pollution, Public Service, and Under-Five Mortality: A Cross-Country Empirical Study. *Healthcare, 8*(3), 271.
28. Liu, Y., Liu, K., Zhang, X., & Guo, Q. (2024). Does digital infrastructure improve public Health? A quasi-natural experiment based on China's Broadband policy. *Social Science & Medicine, 344,* 116624.
29. Luechinger, S. (2014). Air pollution and infant mortality: A natural experiment from power plant desulfurization. *Journal of Health Economics, 37,* 219–231.
30. Luo, J., Du, P., Samat, A., Xia, J., Che, M., & Xue, Z. (2017). Spatiotemporal Pattern of PM2.5 Concentrations in Mainland China and Analysis of Its Influencing Factors using Geographically Weighted Regression. *Scientific Reports, 7*(1), 40607.
31. Maisonet, M., Bush, T. J., Correa, A., & Jaakkola, J. J. (2001). Relation between ambient air pollution and low birth weight in the Northeastern United States. *Environmental Health Perspectives, 109*(suppl 3), 351–356.
32. Marmot, M. (2020). Health equity in England: the Marmot review 10 years on. *Bmj,* 368.
33. Nair, M., Kurinczuk, J. J., Brocklehurst, P., Sellers, S., Lewis, G., & Knight, M. (2015). Factors associated with maternal death from direct pregnancy complications: a UK national case–control study. *BJOG: An International Journal of Obstetrics & Gynaecology, 122*(5), 653-662.
34. Phelan, J. C., Link, B. G., & Tehranifar, P. (2010). Social conditions as fundamental causes of health inequalities: theory, evidence, and policy implications. *Journal of health and social behavior, 51*(1_suppl), S28-S40.
35. Pleasant, A., Cabe, J., Patel, K., Cosenza, J., & Carmona, R. (2015). Health literacy research and practice: A needed paradigm shift. *Health Communication, 30*(12), 1176-1180.
36. Qian, X., Ding, H., & Ding, Z. (2023). Governmental inspection and firm environmental protection expenditure: Evidence from China. *Economic Modelling, 123,* 106284.
37. Qin, Y., Sun, C., Li, D., Zhang, H., Wang, H., & Duan, Y. (2023). Does urban air pollution have an impact on public health? Empirical evidence from 288 prefecture-level cities in China. *Urban Climate, 51,* 101660.
38. Schulte, K., & Hudson, B. (2023). A cross-sectional study of inequalities in digital air pollution information access and exposure reducing behavior uptake in the UK. *Environment International, 181,* 108236.
39. Shao, Q., & Shen, S. (2017). When reduced working time harms the environment: A panel threshold analysis for EU-15, 1970–2010. *Journal of Cleaner Production, 147*, 319–329.

40. Sieck, C. J., Sheon, A., Ancker, J. S., Castek, J., Callahan, B., & Siefer, A. (2021). Digital inclusion as a social determinant of health. *NPJ digital medicine, 4*(1), 52.
41. United Nations Children's Fund. (2021). *Futures at risk: COVID-19 disruptions to maternal, newborn and child health and nutrition services in fragile and conflict-affected settings.* UNICEF UK.
42. Vardoulakis, S., Jalaludin, B. B., Morgan, G. G., Hanigan, I. C., & Johnston, F. H. (2020). Bushfire smoke: urgent need for a national health protection strategy. *The Medical Journal of Australia, 212*(8), 349.
43. Wang, Q., Kwan, M.-P., Zhou, K., Fan, J., Wang, Y., & Zhan, D. (2019). The impacts of urbanization on fine particulate matter (PM2.5) concentrations: Empirical evidence from 135 countries worldwide. *Environmental Pollution, 247*(0).
44. Wang, Y., Huang, X., Zhang, T., Jiang, B., & Wang, X. (2024). Impact of fiscal decentralization and local government competition on the supply of basic public services: Based on the empirical evidence of prefecture-level cities in China. *Heliyon, 10*(4), e26511.
45. Wang, Y., Sun, K., Li, L., Lei, Y., Wu, S., Jiang, Y., Mi, Y., & Yang, J. (2022). The impacts of economic level and air pollution on public health at the micro and macro level. *Journal of Cleaner Production, 366,* 132932.
46. World Health Statistics. (n.d.). Retrieved May 3, 2025, from https://www.who.int/data/gho/publications/world-health-statistics.
47. Wu, H., Ba, N., Ren, S., Xu, L., Chai, J., Irfan, M., Hao, Y., & Lu, Z.-N. (2022). The impact of internet development on the health of Chinese residents: Transmission mechanisms and empirical tests. *Socio-Economic Planning Sciences, 81,* 101178.
48. Xu, L., Feng, K., & Shao, S. (2024). Impacts of air pollution on child growth: Evidence from extensive data in Chinese counties. *Global Environmental Change, 85,* 102808.
49. Yang, X., Wu, H., Ren, S., Ran, Q., & Zhang, J. (2021). Does the development of the internet contribute to air pollution control in China? Mechanism discussion and empirical test. *Structural Change and Economic Dynamics, 56,* 207–224.
50. Zhong, M., Qiang, D., Wang, J., & Sun, W. (2024). Improving health and reducing health inequality: An innovation of digitalization? *Social Science & Medicine, 348,* 116847.

Figures

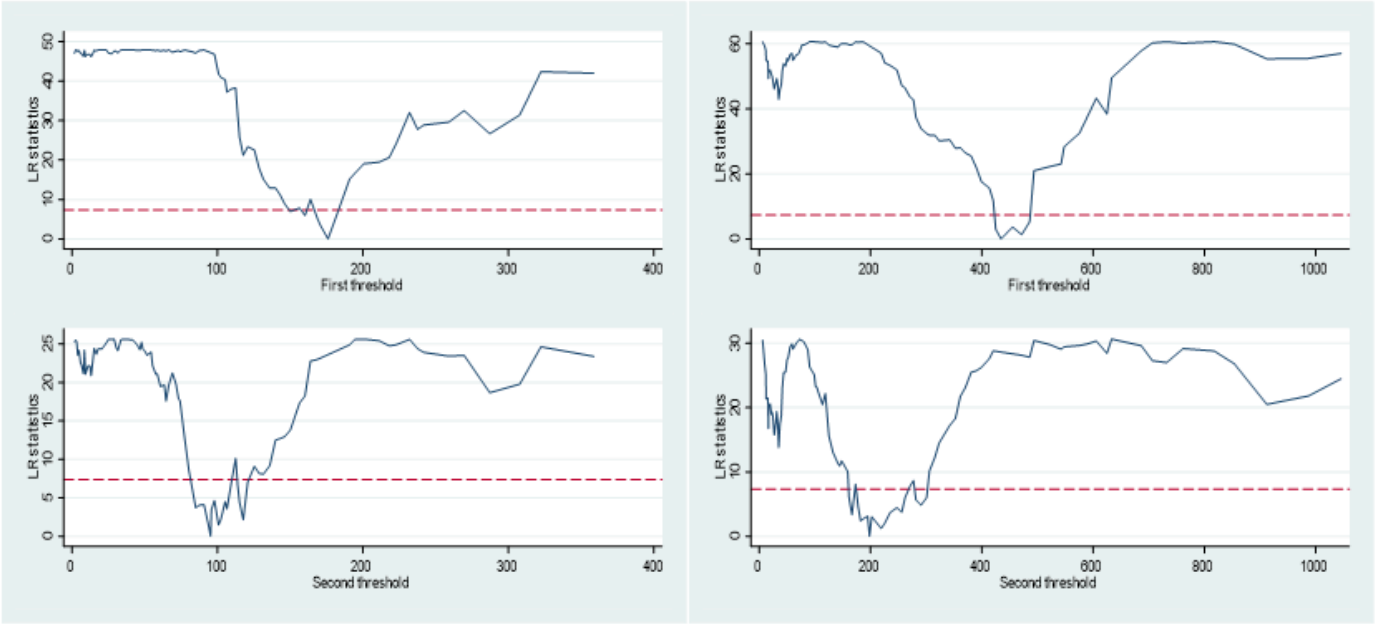


Figure 1

Medical and health, Environmental protection thresholds and likelihood ratio functions.

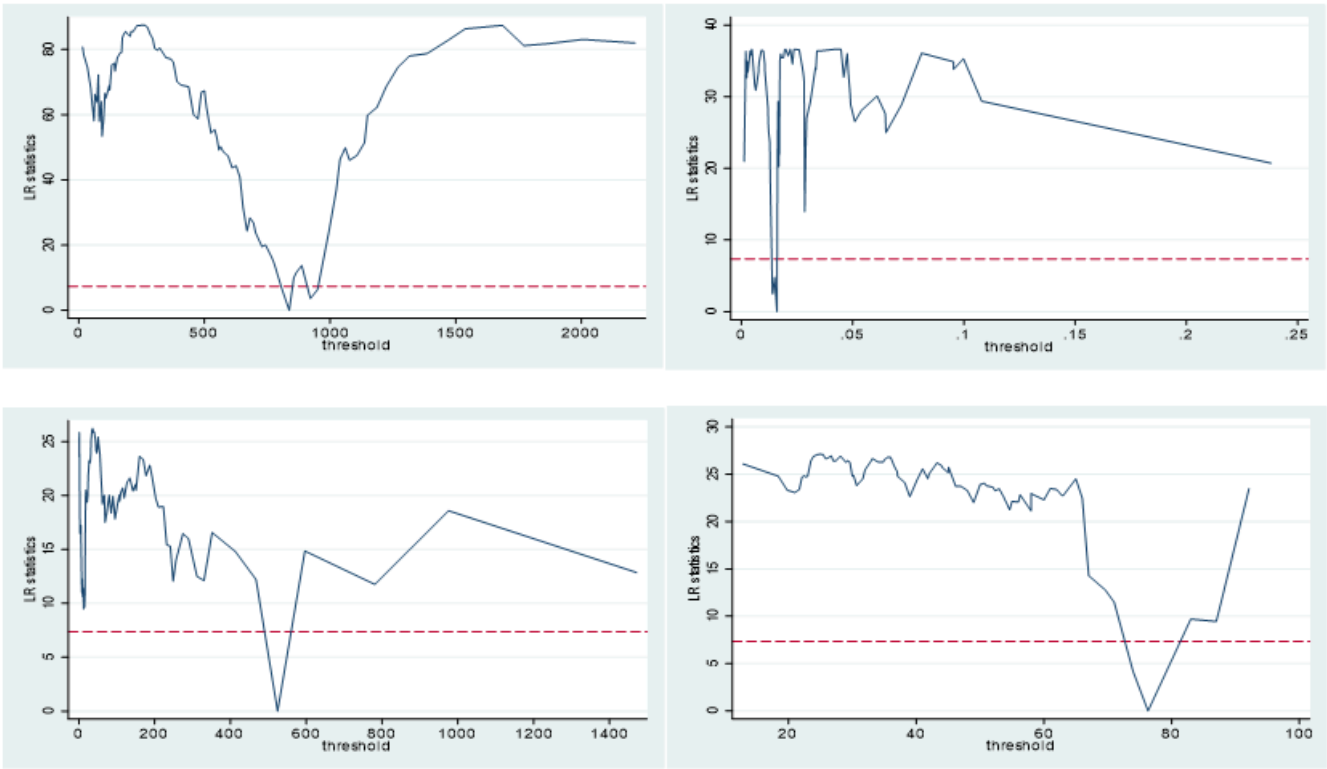


Figure 2

Public education, Internet infrastructure, Internet applications, Internet information resources thresholds and likelihood ratio functions.