Study on the Coverage and Influencing Factors of Human Papillomavirus Vaccine among Eligible Populations in China Based on Geographically Weighted Regression Models (Postprint)

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Abstract

Abstract

Background: Cervical cancer is the fourth most common malignant tumor among women globally, and persistent infection with high-risk human papillomavirus (HR-HPV) is its necessary cause. HPV vaccination can effectively prevent cervical cancer; however, the HPV vaccination coverage rate in China is far below the 90% target proposed by the WHO. Currently, research on the factors influencing HPV vaccination coverage is insufficient, and this study can accumulate evidence for research in this field.

Objective: To explore the spatial relationship between HPV vaccination coverage and its influencing factors among the age-eligible population in China, providing a scientific basis for different provincial administrative regions to formulate HPV vaccination strategies that align with local realities.

Methods: The dependent variable of this study is the HPV vaccination coverage rate of various provincial administrative regions in China in 2022, derived from data released by the Chinese Center for Disease Control and Prevention. The independent variables cover two major categories—socioeconomic level and health indicators—comprising a total of 10 variables [female junior middle school education rate, female senior high school education rate, female higher education rate, female illiteracy rate, female employment rate, proportion of female ethnic minority population, proportion of female rural population, per capita disposable income, per capita healthcare expenditure, and the number of community health service centers (stations)], sourced from the Seventh National Population Census, the "China Statistical Yearbook 2022," and relevant data released by the National Bureau of Statistics. R 4.1.3 software was used for data processing and general analysis, and a linear regression model was constructed.

ArcGIS 10.8 software was used for global spatial autocorrelation analysis, construction of geographically weighted regression models, hotspot analysis, and the mapping of spatial distributions. The data collection and analysis for this study were completed in April 2025.

Results: The HPV vaccination coverage rate across provincial administrative regions nationwide ranged from 2.55% to 25.4%. Differences in HPV vaccination coverage existed among different provincial administrative regions, exhibiting significant spatial clustering characteristics (Moran' s I index = 0.198, $P = 0.007$), with higher coverage in the southeast and Sichuan-Chongqing regions, and relatively lower coverage in the western regions. HPV vaccination coverage was influenced by female education levels, economic levels, female sociodemographic characteristics, and the number of community health service centers (stations) ($P < 0.05$), and the degree of influence exhibited spatial variations.

Conclusion: HPV vaccination coverage in China shows a phenomenon of being high in the southeast and low in the northwest. The female higher education rate, per capita disposable income, and the proportion of the female rural population are the core reasons for these spatial differences. Government departments can implement a triple policy of "full central government funding, mobile vaccination, and health education promotion"in the western regions; provide economic support for vulnerable populations in the eastern regions; and expand the population eligible for HPV vaccination incentive policies in the central regions while transforming high knowledge levels into high vaccination rates through behavioral incentives. By using precise and localized strategies to improve HPV vaccination coverage, the elimination of cervical cancer can be substantively advanced.

Full Text

Preamble

Research on Human Papillomavirus Vaccine Coverage and Influencing Factors Among Eligible Populations in China Based on Geographically Weighted Regression Models

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Abstract

Human Papillomavirus (HPV) is a primary cause of cervical cancer. While HPV vaccination is an effective preventive measure, coverage rates in China remain low and exhibit significant spatial heterogeneity. This study aims to analyze the spatial distribution of HPV vaccine coverage among eligible populations in China and explore the key influencing factors using a Geographically Weighted Regression (GWR) model. By accounting for regional variations in

socioeconomic status, healthcare accessibility, and public health awareness, this research provides a scientific basis for optimizing vaccination strategies and reducing regional disparities in cervical cancer prevention.

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1. Introduction

Cervical cancer is one of the most common malignant tumors affecting women' s health globally. In China, the incidence and mortality rates of cervical cancer have shown an upward trend in recent years, with a lotable shift toward younger populations. Persistent infection with high-risk types of Human Papillomavirus (HPV) is the fundamental cause of cervical cancer. Consequently, HPV vaccination has become a critical primary prevention strategy.

Since the first HPV vaccine was approved for marketing in mainland China in 2016, the variety of available vaccines (2-valent, 4-valent, and 9-valent) has increased. However, despite the expansion of immunization services, the overall coverage rate among the target population—particularly adolescent girls and young women—remains insufficient to meet the goals set by the World Health Organization' s (WHO) global strategy to accelerate the elimination of cervical cancer.

Previous studies have indicated that HPV vaccination behavior is influenced by a complex interplay of individual, social, and structural factors. However, most existing research relies on traditional global regression models, which assume that the relationships between independent and dependent variables are stationary across space. Given China' s vast territory and the significant disparities in economic development and healthcare resource distribution between eastern, central, and western regions, it is highly likely that the factors influencing HPV vaccination exhibit spatial non-stationarity.

This study utilizes a Geographically Weighted Regression (GWR) model to examine the spatial distribution of HPV vaccine coverage across various provinces in China. By incorporating spatial coordinates into the regression framework, the GWR model allows for the estimation of localized coefficients, thereby revealing how the impact of socioeconomic and healthcare factors varies geographically. The findings of this study aim to provide targeted policy recommendations for improving

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Abstract

Background Cervical cancer is the fourth most common malignancy among women globally, with persistent infection by high-risk human papillomavirus (HR-HPV) serving as its primary causative factor. While HPV vaccination

effectively prevents cervical cancer, the coverage rate in China remains significantly lower than the 90% target proposed by the World Health Organization (WHO). Currently, research on the factors influencing HPV vaccine coverage is insufficient; this study aims to accumulate evidence to address this gap.

Objective To explore the spatial relationship between HPV vaccine coverage and its influencing factors among the eligible population in China, providing a scientific basis for provincial administrative regions to formulate localized HPV vaccination strategies.

Methods The dependent variable for this study was the 2022 HPV vaccine coverage rate across various provincial administrative regions in China, sourced from data released by the Chinese Center for Disease Control and Prevention. Ten independent variables were selected across two categories: socioeconomic status and health indicators. These included female junior high school education rate, female senior high school education rate, female higher education rate, female illiteracy rate, female employment rate, proportion of female ethnic minority population, proportion of female rural population, per capita disposable income, per capita healthcare expenditure, and the number of community health service centers (stations). Data were obtained from the Seventh National Census, the *China Statistical Yearbook 2022*, and relevant datasets from the National Bureau of Statistics. Data processing and general analysis were performed using R 4.1.3. Linear regression models were constructed, and ArcGIS 10.8 was utilized for global spatial autocorrelation analysis, hot spot analysis, and the construction of Geographically Weighted Regression (GWR) models to map spatial distributions. Data collection and analysis were completed in April 2025.

Results HPV vaccine coverage across provincial administrative regions ranged from 2.55% to 25.4%. Coverage rates varied significantly by region and exhibited distinct spatial clustering (Moran's I = 0.198, $P = 0.007$). Higher coverage rates were observed in Southeast China and the Sichuan-Chongqing region, while rates were relatively lower in Western China. HPV vaccine coverage was significantly influenced by female education levels, economic status, female sociodemographic characteristics, and the number of community health service centers ($P < 0.05$), with the degree of influence exhibiting spatial heterogeneity.

Conclusion HPV vaccine coverage in China demonstrates a spatial pattern of being higher in the southeast and lower in the northwest. The female higher education rate, per capita disposable income, and the proportion of the female rural population are the core drivers of these spatial differences. Government departments should consider a "triple policy" for Western China involving full central government funding, mobile vaccination units, and targeted health education. In Eastern China, financial support should be provided to vulnerable populations. In Central China, preferential vaccination policies should be expanded, and behavioral incentives should be used to translate high knowledge levels into actual vaccination rates. By employing precise, localized strategies, China can improve HPV vaccine coverage and substantially advance the elimi-

nation of cervical cancer.

Keywords: Papillomavirus vaccines; Vaccination coverage; Geographically weighted regression model; Socioeconomic factors; Root cause analysis

Current research on factors influencing HPV vaccine coverage is insufficient. This study aims to contribute evidence to this field.

Research on Human Papillomavirus Vaccine Coverage and Influencing Factors Among Eligible Populations in China Based on Geographically Weighted Regression Models

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Abstract

Objective: To explore the spatial relationships between Human Papillomavirus (HPV) vaccine coverage and its influencing factors among the eligible population in China.

Introduction

Cervical cancer remains a significant global public health challenge, being one of the most common malignancies affecting the female reproductive system. Persistent infection with high-risk types of Human Papillomavirus (HPV) is the primary causative factor for cervical cancer. Vaccination against HPV is recognized as the most effective primary prevention strategy to reduce the incidence of cervical cancer and related diseases.

In recent years, China has made substantial efforts to promote HPV vaccination. However, vaccine coverage rates continue to exhibit significant regional disparities due to variations in socioeconomic development, healthcare resource allocation, and public awareness. Understanding the spatial distribution of HPV vaccine coverage and identifying the localized factors that influence uptake is crucial for formulating targeted public health interventions.

Traditional global regression models often assume that the relationships between independent and dependent variables are stationary across space. However, in a country as geographically and socioeconomically diverse as China, these relationships are likely to exhibit spatial non-stationarity. Therefore, this study utilizes the Geographically Weighted Regression (GWR) model to analyze the

spatial heterogeneity of HPV vaccine coverage and its driving factors among the eligible population.

Methods

Data Sources

The data for this study were collected from national health statistics, provincial immunization programs, and socioeconomic indicators provided by the National Bureau of Statistics. The study population includes females within the age range recommended for HPV vaccination according to national guidelines.

Statistical Analysis

Spatial autocorrelation was first assessed using Global Moran's I to determine if HPV vaccine coverage exhibited significant spatial clustering. Subsequently, a Geographically Weighted Regression (GWR) model was constructed to explore how the impact of various factors—such as regional GDP per capita, the density of healthcare facilities, and educational attainment—varies across different geographical regions.

The GWR model is expressed as:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i) x_{ik} + \epsilon_i$$

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population in China, and to provide a scientific basis for formulating region-specific HPV vaccination strategies tailored to the actual conditions of different provincial-level administrative regions. Methods: The dependent variable was derived from the 2022 regional statistics on HPV vaccine coverage released by the Chinese Center for Disease Control and Prevention. Independent variables were obtained from the Seventh National Population Census, the China Statistical Yearbook 2022, and the National Bureau of Statistics, covering 10 continuous variables across two categories: socioeconomic level and health indicators. These included female junior high school, senior high school, and higher education rates; female illiteracy rate; female employment rate; proportion of ethnic minority women; proportion of rural women; per capita disposable income; per capita healthcare expenditure; and number of community health service centers (stations). All variables were included in the model in their original form. Data processing and general analysis were performed using R software, and a

linear regression model was constructed. Global spatial autocorrelation analysis, geographically weighted regression (GWR) modeling, and hotspot analysis were conducted using ArcGIS software, with spatial distribution maps generated. Data collection and analysis were completed in April 2025. Results: The HPV vaccine coverage rates across provinces ranged from 2.55% to 25.4%. Significant differences in coverage were observed among provincial-level administrative regions, exhibiting distinct spatial clustering characteristics (Moran' s I index = 0.198, $P = 0.007$).

Coverage was higher in southeastern regions and the Sichuan-Chongqing area, while relatively lower in western regions. HPV vaccine coverage was influenced by female education level, economic status, female sociodemographic characteristics, and the number of community health service centers (stations) ($P < 0.05$), with varying degrees of impact across different geographical areas. Conclusion: HPV vaccine coverage in China demonstrates a spatial pattern of being higher in the southeast and lower in the northwest. Female higher education rates, per capita disposable income, and the proportion of rural women are the core factors contributing to this spatial disparity. A triple policy of "central government full funding, mobile vaccination units, and health education campaigns"could be implemented in western regions. Eastern regions should provide economic support for disadvantaged populations. Central regions could expand eligibility for HPV vaccination subsidies and convert high health literacy into higher vaccination rates through behavioral incentives. Adopting precise, localized strategies will enhance HPV vaccine coverage and substantially advance the elimination of cervical cancer.

【Key words】 Papillomavirus vaccines; Vaccination coverage; Geographically weighted regression model; Socioeconomic factors; Root cause analysis

Cervical cancer is the fourth most common malignant tumor and the fourth leading cause of cancer-related death among women globally [**?**]. In 2022, China had approximately 151,000 new cases of cervical cancer and 56,000 deaths, accounting for 22.8% and 16% of the global incidence and mortality, respectively; it remains the fifth most common malignant tumor and the sixth leading cause of cancer death among Chinese women [**?**]. Persistent infection with high-risk human papillomavirus (HR-HPV) is the necessary cause of cervical cancer [**?**]. Consequently, the combination of HPV screening every five years and prophylactic HPV vaccination represents the most cost-effective cervical cancer prevention strategy for China [**?**]. Research indicates that when HPV vaccine coverage exceeds 50%, cross-protection and herd immunity effects emerge [**?**], effectively reducing HPV infection and transmission, thereby lowering the incidence of cervical cancer. To eliminate···

分析法是借助地理信息系统（GIS）技术，对空间数据

Processing and analysis are conducted to reveal the distribution, relationships, and underlying patterns of geographical phenomena.

方法 [8]。本研究借助 ArcGIS 软件的空间分析法，揭示

This study aims to characterize the geographical distribution of Human Papillomavirus (HPV) vaccine coverage across different regions and explore the varying impacts of socioeconomic status and health indicators on these coverage rates. By analyzing these regional disparities, the research provides a scientific foundation for provincial administrative regions in China to develop HPV vaccination strategies for eligible populations that are tailored to their specific local conditions.

1.1 资料来源

The study area encompasses 31 provincial-level administrative regions in mainland China, excluding the Hong Kong Special Administrative Region, the Macao Special Administrative Region, and Taiwan Province. To eliminate cervical cancer, the World Health Organization (WHO) established a global target in 2020: by the year 2030, 90% of girls should be fully vaccinated against HPV by the age of 15 [**?**], representing an HPV vaccine coverage rate of 90%. Between 2017 and 2022, the HPV vaccine coverage rate among the eligible population in China increased annually. All data utilized in this study consist of annual figures for 2022, with data collection and analysis conducted in 2025.

4 月完成。

The research factors are categorized into two primary dimensions: socioeconomic indicators and health indicators. (1) Socioeconomic indicators comprise three categories: female education level, female sociodemographic proportions, and economic status. Specifically, female education indicators include the rates of junior high school, senior high school, and higher education, as well as the female illiteracy rate. Female sociodemographic indicators include the female employment rate, the proportion of ethnic minority women, and the proportion of the female rural population. Economic indicators include per capita disposable income and per capita healthcare expenditure. (2) The health indicator is represented by the number of community health service centers (stations), which reflects the coverage and accessibility of the primary healthcare service network. Although the HPV vaccination rate has increased from 0.01% to 10.15%, the overall coverage remains suboptimal. There is a significant gap compared to the 90% vaccination target proposed by the WHO, and regional disparities are pronounced—with the highest coverage in the eastern region and relatively lower rates in the western region [**?**]. This phenomenon may be closely related to various factors, including regional economic development, educational resources, medical insurance systems, and sociocultural backgrounds.

Currently, there is a lack of systematic research and in-depth exploration regarding how the influence of these factors on HPV vaccination coverage varies across different regions. Spatial hotspots and coldspots are identified at a 90% confidence level, alongside non-significant areas. In this context, a hotspot in-

dicates that an independent variable in that region has a significant impact on HPV vaccination coverage.

The specific data sources are as follows: Data on HPV vaccine coverage across China' s provincial administrative regions were obtained from relevant statistics released by the Chinese Center for Disease Control and Prevention in 2024 [**?**]. Female illiteracy rates and per capita disposable income were sourced from the *China Statistical Yearbook 2022* [**?**]. Data regarding female junior high, senior high, and higher education rates, the proportion of ethnic minority women, the proportion of the female rural population, the female employment rate, and per capita healthcare expenditure were derived from the *Seventh National Population Census* [**?**]. Finally, the number of community health service centers (stations) was obtained from 2022 data released by the National Bureau of Statistics [**?**].

1.2.1 全局空间自相关分析

This methodology is used to evaluate the spatial distribution characteristics of HPV vaccine coverage across 31 provincial-level administrative regions. The Moran' s I index was employed as the measure for global spatial autocorrelation.

分析的主要指标，来衡量空间自相关程度，取值范围

The value ranges from -1 to 1. If the Moran's I index is greater than 0, it indicates that HPV vaccine coverage exhibits spatial clustering across the country; that is, provincial administrative regions with high coverage rates tend to cluster together, while those with low coverage rates also tend to be geographically proximate. Conversely, if the Moran' s I index is less than 0, it represents a spatially dispersed distribution. If the Moran' s I index is close to 0, it suggests that the spatial distribution of HPV vaccination rates is random [**?**].

1.2.2 线性回归模型及地理加权回归模型（GWR）

Conversely, cold spots indicate that the correlation between a specific independent variable and HPV vaccine coverage in that region is weak or non-significant [**?**]. This analytical approach enables researchers to precisely identify the key factors influencing HPV vaccine coverage across different regions, thereby providing a scientific basis for the formulation of public health policies.

1.3 统计学方法

Data processing and analysis were conducted using R version 4.1.3, which was also employed to construct the linear regression models. ArcGIS 10.8 was utilized to perform global spatial autocorrelation analysis, develop the Geographically Weighted Regression (GWR) models, and conduct hot spot analysis. Additionally, ArcGIS was used to generate all spatial distribution maps.

2.1 HPV 疫苗覆盖率、社会经济水平和卫生指标的基

HPV vaccine coverage rates across provincial-level administrative regions range from 2.55% to 25.4%, with an average coverage rate of 9.62%, indicating significant regional disparities. Geographically, coverage rates are higher in Southeast China and the Sichuan-Chongqing region, while remaining lower in Western China. The top three regions for HPV vaccine coverage are Beijing (25.400%), Shanghai (20.990%), and Guangdong Province (15.460%).

The three regions with the lowest coverage rates are Gansu Province (3.410%), Qinghai Province (2.950%), and the Xinjiang Uyghur Autonomous Region (2.550%), as shown in [Figure 1: see original paper]. The socioeconomic status and health indicators for the various provincial-level administrative regions are detailed in .

Using the 2022 provincial-level HPV vaccine coverage rates published in the *China CDC Weekly* as the dependent variable, a linear regression model was constructed to identify independent variables significantly influencing coverage ($P < 0.05$). The independent variables (all treated as continuous variables) included: female junior high school education rate, female senior high school education rate, female higher education rate, female illiteracy rate, per capita disposable income, per capita healthcare expenditure, female employment rate, proportion of female ethnic minority population, proportion of female rural population, and the number of community health service centers (stations).

A Geographically Weighted Regression (GWR) model was subsequently developed by taking the HPV vaccine coverage rate as the dependent variable and incorporating the independent variables that demonstrated statistical significance ($P < 0.05$) in the linear regression model. The global Adjusted R^2 was used to reflect the overall explanatory power and goodness-of-fit of the GWR model, while the local Adjusted R^2 reflected the model' s performance within each specific provincial-level administrative region. The bandwidth was utilized to define the local scope and reflect model smoothness. Additionally, the Residual Sum of Squares (RSS) was used to measure the total prediction error, the corrected Akaike Information Criterion (AICc) was employed to assess the balance between model fit and complexity, and regression coefficients were used to evaluate the specific impact of the studied factors on HPV vaccine coverage.

1.2.3 热点分析

This is a local spatial autocorrelation analysis method used to identify clusters of high values (hot spots) and low values (cold spots) within spatial data. By performing hot spot analysis on the regression coefficients derived from Geographically Weighted Regression (GWR) and utilizing confidence intervals as indicators, one can intuitively visualize the spatial distribution characteristics of the independent variables' influence on the dependent variable.

The confidence intervals are categorized into seven distinct levels: hot spots

and cold spots at the 99% confidence level, hot spots and cold spots at the 95% confidence level, hot spots and cold spots at the 90% confidence level, and areas that are not statistically significant.

[Figure 2024: see original paper] Note: The map is downloaded from the National Platform for Common Geo-Spatial Information Services (Tianditu) 2024 edition; Map Approval Number: [Pending/Omitted].

GS (2024) No. 0650.

[Figure 1: see original paper] **Figure 1 Distribution of HPV vaccine coverage rate in China (2022)**

Table 1 Basic characteristics of socioeconomic status and health indicators across 31 provincial-level administrative regions

Provincial-level Administrative Region	Female Junior Middle School Education Rate (%)	Female High School Education Rate (%)	Female Higher Education Rate (%)	Per Capita Disposable Income (Yuan)	Per Capita Healthcare Expenditure (Yuan)	Proportion of Female Ethnic Minority Population	Proportion of Female Rural Population
Xinjiang Uygur Autonomous Region						0.367	
Tibet Autonomous Region							
Inner Mongolia Autonomous Region							

Provincial-level Administrative Region	Female Junior Middle School Education Rate (%)	Female High School Education Rate (%)	Female Higher Education Rate (%)	Per Capita Disposable Income (Yuan)	Per Capita Healthcare Expenditure (Yuan)	Proportion of Female Ethnic Minority Population	Proportion of Female Rural Population
Ningxia Hui Autonomous Region							
Guangxi Zhuang Autonomous Region							

Note: Provincial-level administrative regions are sorted in ascending order according to their HPV vaccine coverage rates.

Community Health Service Centers (Stations)

2.2 空间异质性分析

The results indicate that HPV vaccine coverage exhibits a positive spatial autocorrelation (Moran' s I = 0.198, P = 0.007). This suggests that regions with higher HPV vaccine coverage tend to be geographically clustered. Furthermore, this clustering phenomenon is not randomly distributed but represents a statistically significant characteristic of the spatial data.

2.3 线性回归模型

The results of the linear model indicate that several factors have a statistically significant impact on HPV vaccination coverage ($P < 0.05$). These factors include the female high school education rate, female higher education rate, female illiteracy rate, per capita disposable income, per capita healthcare expenditure, the proportion of the female ethnic minority population, the proportion of the female rural population, and the number of community health service centers (stations). Conversely, the female junior high school education rate and the female employment rate did not show a statistically significant effect on HPV vaccination coverage ($P > 0.05$). Detailed results are presented in Table 2 .

2.4 地理加权回归模型与热点分析

Table 2: Linear Regression Model Analysis of Factors Influencing HPV Vaccine Coverage in China

Variable	P-value
Female Junior Middle School Education Rate	<0.001
Female Senior High School Education Rate	<0.001
Female Higher Education Rate	<0.001
Female Illiteracy Rate	<0.001
Per Capita Disposable Income	<0.001
Per Capita Healthcare Expenditure	<0.001
Female Employment Rate	<0.001
Proportion of Female Ethnic Minority Population	<0.001
Proportion of Female Rural Population	<0.001
Number of Community Health Service Centers (Stations)	<0.001

2.4.1 女性受教育水平

In regions such as the Xinjiang Uygur Autonomous Region and the Tibet Autonomous Region, the promoting effects of per capita disposable income, female high school education rates, and female illiteracy rates on HPV vaccine coverage are particularly pronounced.

In the Inner Mongolia Autonomous Region, Ningxia Hui Autonomous Region, Shanxi Province, Hebei Province, Beijing, Tianjin, Shandong Province, and Liaoning Province, the promoting effect of per capita healthcare expenditure on HPV vaccine coverage is particularly significant. Conversely, in the Tibet Autonomous Region, Guangxi Zhuang Autonomous Region, and Hainan Province, the impact of per capita healthcare expenditure on HPV vaccine coverage is relatively small ([Figure 2: see original paper], 3). While some factors show weaker explanatory power for coverage rates, the female higher education rate serves as a robust explanatory variable for variations in HPV vaccine coverage (). Specifically, the regression coefficients for female high school education rates and female higher education rates are positive, indicating that HPV vaccine coverage tends to increase as women' s education levels rise.

In contrast, the regression coefficient for the female illiteracy rate is negative, suggesting that an increase in the female illiteracy rate leads to a decrease in HPV vaccine coverage ().

2.4.3 女性社会人口学比例

In the Xinjiang Uygur Autonomous Region, Gansu Province, and the Ningxia Hui Autonomous Region, the proportion of the female rural population serves

as a strong explanatory variable for variations in HPV vaccine coverage. Conversely, the proportion of the female ethnic minority population demonstrates a weaker explanatory capacity regarding HPV vaccine coverage (Table 3). The regression coefficients for these variables are consistently negative, indicating that as the proportions of the female rural population and female ethnic minority population increase, HPV vaccine coverage tends to decrease (Table 4). Across all provincial-level administrative regions, the proportion of the female ethnic minority population does not exert a significant independent effect on HPV vaccine coverage.

The promotion of female high school education rates has a substantial positive impact on increasing HPV vaccine coverage. However, in Jilin, Jiangsu, Anhui, and Zhejiang provinces, the influence of female high school education rates is relatively smaller. In the Xinjiang Uygur Autonomous Region, the impact of female higher education rates on the improvement of HPV vaccine coverage is also limited. In Jilin, Liaoning, Hebei, Beijing, Tianjin, Shandong, Henan, Jiangsu, Anhui, Zhejiang, and Fujian, the female illiteracy rate has a strong inhibitory effect on HPV vaccine coverage. In the Xinjiang Uygur Autonomous Region, Tibet Autonomous Region, and Qinghai Province, the negative impact of the female rural population proportion on HPV vaccine coverage is particularly pronounced ([Figure 2: see original paper], [Figure 3: see original paper]).

In the Xinjiang Uygur Autonomous Region, Tibet Autonomous Region, Qinghai Province, Sichuan Province, Gansu Province, and the Ningxia Hui Autonomous Region,

2.4.4 卫生指标

The female illiteracy rate has a relatively minor impact on HPV vaccine coverage (Figures 2 and 3). In contrast, the number of community health service centers (stations) exerts a significant influence on HPV vaccine coverage.

2.4.2 经济水平

The explanatory power of these variables is relatively weak (Table 3). Within each provincial administrative region, the regression coefficients for per capita disposable income and per capita healthcare expenditure demonstrate strong explanatory power regarding changes in HPV vaccine coverage (Table 3). These coefficients are consistently positive, indicating that increases in per capita disposable income and healthcare expenditure promote higher HPV vaccine coverage (Table 4). Furthermore, the number of community health service centers (stations) also shows positive regression coefficients, suggesting that an expansion of these facilities facilitates an increase in HPV vaccine coverage (Table 4). This promotional effect of community health service centers (stations) on HPV vaccine coverage is particularly pronounced in the Xinjiang Uygur Autonomous Region (Figures 2 and 3).

Table 3 Parameters of the GWR model for factors influencing HPV vaccine coverage rate in China Global Adjusted R^2 (a); Local Adjusted R^2 (b) Minimum; Local Adjusted R^2 Maximum; Bandwidth; Female high school education rate; Female higher education rate; Female illiteracy rate; Per capita disposable income; Per capita healthcare expenditure; Proportion of female ethnic minority population; Proportion of female rural population; Number of community health service centers (stations). Note: GWR = Geographically Weighted Regression model; (a) represents the overall fitting coefficient of the GWR model; (b) represents the fitting coefficients of the GWR model within each provincial administrative region.

Table 4 Geographically weighted regression coefficient estimates Female high school education rate; Female higher education rate; Female illiteracy rate.

第一四分位数

Per capita disposable income, per capita healthcare expenditure, the proportion of the female ethnic minority population, the proportion of the female rural population, and the number of community health service centers (stations) 0.000 33

第三四分位数

Note: Maps were downloaded from the 2024 version of Tianditu, National Platform for Common Geospatial Information Services, Map Approval No. GS (2024) 0650. Figure A shows the spatial distribution of regression coefficients for the female high school education rate; Figure B shows the spatial distribution of regression coefficients for the female higher education rate; Figure C shows the spatial distribution of regression coefficients for the female illiteracy rate; Figure D shows the spatial distribution of regression coefficients for per capita disposable income; Figure E shows the spatial distribution of regression coefficients for per capita healthcare expenditure; Figure F shows the spatial distribution of regression coefficients for the proportion of the female rural population; Figure G shows the spatial distribution of regression coefficients for the proportion of the female ethnic minority population; Figure H shows the spatial distribution of regression coefficients for the number of community health service centers (stations).

Figure 2: Spatial distribution of regression coefficients for influencing factors. Note: Maps were downloaded from the 2024 version of Tianditu, National Platform for Common Geospatial Information Services, Map Approval No. GS (2024) 0650. Figure A presents the hot spot analysis of regression coefficients for the female high school education rate; Figure B presents the hot spot analysis for the female higher education rate; Figure C presents the hot spot analysis for the female illiteracy rate; Figure D presents the hot spot analysis for per capita disposable income; Figure E presents the hot spot analysis for per capita healthcare expenditure; Figure F presents the hot spot analysis for the proportion of

the female rural population; Figure G presents the hot spot analysis for the proportion of the female ethnic minority population; Figure H presents the hot spot analysis for the number of community health service centers (stations).

Figure 3 [Figure 3: see original paper] Spatial hot spot analysis of factor effects on HPV vaccine coverage. This study innovatively employs the Geographically Weighted Regression (GWR) model to reveal the spatial distribution characteristics of HPV vaccine coverage and its influencing factors in China. The results indicate that HPV vaccine coverage varies across different provincial-level administrative regions and exhibits significant spatial clustering. Coverage is influenced by factors such as female education levels, economic status, female socio-demographic characteristics, and the number of community health service centers (stations). Furthermore, the impact of these factors on coverage across different provinces demonstrates spatial heterogeneity, suggesting that regional factors play a critical role in vaccine promotion. Among these, per capita disposable income, female higher education rates, per capita healthcare expenditure, and the proportion of the female rural population exert the most substantial influence. Utilizing spatial analysis at the provincial level to evaluate these factors provides a scientific basis for formulating targeted public health policies, optimizing resource allocation, increasing vaccination rates, and reducing health inequities caused by regional disparities.

The coverage of the HPV vaccine exhibits distinct spatial clustering, suggesting that shared regional factors may act collectively across different areas to influence vaccination behavior. HPV vaccine coverage is generally higher in eastern coastal urban clusters, while coverage in five western provinces (Tibet Autonomous Region, Qinghai, Gansu, Yunnan, and Guizhou) remains at the lowest levels. This disparity is not merely a result of economic gaps but is a complex outcome of the coupled effects of policy, medical resources, and cultural systems. Among these, policy differences represent the "exogenous shock" with the strongest explanatory power.

Since 2021, several eastern regions, including Guangdong, Zhejiang, and Jiangsu provinces, have incorporated the HPV vaccine into local public welfare projects. In these areas, local governments fully cover the cost of the two-dose vaccine series for 14-year-old females or provide financial subsidies [**?**]. Government endorsement not only lowers the economic threshold for vaccination but also enhances the credibility of media publicity and physician recommendations. In contrast, western provinces are constrained by local fiscal limitations; central transfer payments are only sufficient to maintain the operation of the National Immunization Program, leaving these regions unable to include the HPV vaccine in local welfare policies. Consequently, individuals must bear the full cost of the vaccine, which serves as the primary barrier to increasing coverage and results in rates significantly lower than those in eastern coastal clusters. Further application of spatial analysis to examine the regional impact of socioeconomic levels and healthcare indicators on HPV vaccine coverage can assist central and local governments in optimizing resource allocation based on actual conditions.

This approach facilitates the development of refined vaccination implementation plans, ultimately reducing health inequities arising from regional disparities.

3.1 教育水平的影响

Research findings indicate that educational attainment has a positive impact on HPV vaccine coverage. Specifically, increases in the rates of both higher education and high school education among women contribute to higher HPV vaccine coverage, whereas an increase in female illiteracy rates leads to a decrease in coverage. These results are consistent with previous studies, which suggest that the educational level of age-eligible women is closely correlated with their awareness and acceptance of the HPV vaccine. Individuals with higher levels of education tend to have a deeper understanding of the vaccine' s importance, are more willing to seek vaccination proactively, and possess better access to health information and medical services [**?**].

Furthermore, this study demonstrates that female higher education has a more significant impact on HPV vaccine coverage than high school education. This aligns with existing research showing that women who have received higher education exhibit higher awareness and vaccination intentions compared to those who have only completed high school [**?**]. This disparity exists because individuals with higher education possess a more comprehensive understanding of the HPV vaccine, encompassing its scientific principles, preventive efficacy, and safety profile. They are also more adept at accessing accurate information through diverse channels, such as academic literature and the internet. Such in-depth knowledge helps dispel misunderstandings and concerns, thereby significantly increasing the willingness to be vaccinated. In contrast, those with only a high school education may have more limited information sources, relying primarily on school curricula and mass media, which may restrict their depth of understanding and accurate perception of the vaccine.

The impact of educational attainment on HPV vaccine coverage varies across different regions. In the Xinjiang Uygur Autonomous Region, Gansu Province, and the Ningxia Hui Autonomous Region, the popularization of high school education plays a stronger role in increasing HPV vaccine coverage. This suggests that these regions should strengthen health education regarding the HPV vaccine during the high school stage to improve the awareness and vaccination intentions of both students and parents. Furthermore, behavioral intervention theories—such as implementing incentives and conducting peer education—should be employed to translate high levels of knowledge into high vaccination rates.

Conversely, in provinces and municipalities such as Jilin, Liaoning, Hebei, Beijing, Tianjin, Shandong, Henan, Jiangsu, Anhui, Zhejiang, and Fujian, the negative impact of illiteracy on HPV vaccine coverage is more pronounced. This indicates that these regions need to focus on the health education needs of populations with lower educational attainment. By utilizing more accessible and easily understood educational methods, these regions can enhance residents'

health consciousness and vaccine literacy, thereby promoting an overall increase in HPV vaccine coverage.

3.2 经济水平的影响

Research findings indicate that regional economic levels have a positive impact on HPV vaccine coverage, with both per capita disposable income and per capita healthcare expenditure contributing to increased coverage rates. This is consistent with previous research: in regions with superior economic conditions, residents are more inclined to invest in their own health [**?**]. High-income populations not only find it easier to afford vaccine costs but also have more convenient access to medical services, which in turn enhances their willingness to be vaccinated and increases overall vaccination rates [**?**].

Currently, HPV vaccination in China has not yet been included in the National Immunization Program and follows the principles of voluntary participation and out-of-pocket payment. However, influenced by factors such as high vaccine prices, supply shortages, and a lot of awareness regarding the vaccine [**?**], the willingness of low-income families to receive the HPV vaccine remains relatively low. An increase in per capita healthcare expenditure signifies an enhanced ability of residents to pay for health-related services, making them more willing to bear the costs associated with vaccination [**?**].

In regions such as the Xinjiang Uygur Autonomous Region and the Tibet Autonomous Region, the promotional effect of per capita disposable income on HPV vaccine coverage is particularly significant. This suggests that in these economically underdeveloped areas, the economic level is a critical factor influencing the willingness to receive the HPV vaccine [**?**].

In response to these findings, the central government should establish a special HPV vaccine assistance fund with a focus on these provinces, prioritizing the inclusion of the HPV vaccine in local "public welfare projects" to provide free vaccinations or high-ratio subsidies (e.g., over 80%) for school-aged girls. Simultaneously, the national government could organize centralized procurement negotiations with vaccine manufacturers to trade volume for lower prices, thereby reducing vaccine costs. In regions such as the Inner Mongolia Autonomous Region, Ningxia Hui Autonomous Region, Shanxi Province, Hebei Province, Beijing, Tianjin, Shandong Province, and Liaoning Province, per capita healthcare expenditure has a substantial impact on HPV vaccine coverage. This indicates that residents in these areas have a higher capacity to pay for and a greater acceptance of the HPV vaccine. Consequently, local governments should further optimize the distribution of medical resources and increase the number of vaccination clinics to improve the accessibility of vaccination services.

3.3 女性社会人口学特征的影响

Update to more comprehensive datasets to improve the applicability and robustness of the model.

3.6 本研究的优势

The proportion of the female ethnic minority population and the proportion of the female rural population exert a negative influence on HPV vaccine coverage. These findings are consistent with previous research:

This study constructed a GWR model based on 2022 national data, which effectively presents the spatial distribution characteristics of HPV vaccine coverage in China. It provides a detailed elaboration on the correlations and spatial specificity between HPV vaccine coverage and factors such as female education levels, economic status, female sociodemographic characteristics, and the number of community health service centers (stations). In areas where ethnic minorities reside, factors such as cultural customs, moral beliefs, religious faith, health perspectives, and the distribution of medical resources can negatively impact HPV vaccination uptake [**?**]. In rural areas, due to limited medical resources and insufficient health education, the acceptance of the HPV vaccine among the rural population is lower than that of the urban population [**?**].

There was no significant difference across regions regarding the reductive effect of the ethnic minority population proportion on HPV vaccine coverage; this is because, under the combined influence of multiple factors such as economic and educational levels, the impact of the ethnic minority population proportion is masked by other variables. In actual HPV vaccine promotion efforts, disease prevention measures can be tailored by integrating the differentiated influencing factors of different provincial-level administrative regions.

HPV vaccine coverage exhibits a distribution characteristic of "high in the southeast and low in the northwest," with significant spatial clustering. Female higher education rates, economic levels, and the proportion of the female rural population are the core driving factors behind these regional differences, and the influence of these factors varies significantly across different provincial-level administrative regions. In areas with a high proportion of rural residents, such as the Xinjiang Uygur Autonomous Region, Tibet Autonomous Region, and Qinghai Province, the rural population proportion has a stronger reductive effect on HPV vaccine coverage. Based on these findings, adopting a uniform national promotion strategy would make it difficult to effectively bridge regional gaps. Therefore, core constraints must be addressed according to each provincial-level administrative region. Local governments should further optimize the allocation of medical resources, increase the supply of HPV vaccines, and improve vaccination accessibility. Simultaneously, they should recruit and train local healthcare workers, teachers, and village heads to serve as health promoters, and produce promotional materials in local languages to enhance residents' trust and acceptance of the vaccine.

3.4 卫生指标的影响

factors to formulate precise, localized intervention measures. In Western regions (such as Xinjiang Uygur Autonomous Region, Tibet Autonomous Region, Qinghai Province, Gansu Province, and Guizhou Province), where economic levels are lower, the proportion of rural population is high, and medical resource accessibility is poor, a "triple policy" is recommended: full central government funding, mobile vaccination services, and health education campaigns.

The number of community health service centers (stations) has a positive impact on HPV vaccine coverage. Previous studies have shown that an increase in the number of community health service centers provides residents with more convenient vaccination channels, thereby promoting HPV vaccination [**?**]. This impact is particularly pronounced in the Xinjiang Uygur Autonomous Region, a region characterized by vast territory, inconvenient transportation, and dispersed residential patterns. To address this, local governments could establish additional fixed vaccination points in remote areas while vigorously developing service models such as mobile vaccination vehicles and itinerant medical teams to provide door-to-door vaccination services in rural and pastoral areas on a regular basis. Furthermore, HPV vaccine consultation and vaccination services could be integrated into existing primary health services—such as maternal health care, adolescent education, and family planning—to improve service efficiency.

In Eastern regions (such as Guangdong, Zhejiang, Jiangsu, Shandong, and Fujian provinces), economic and educational levels are higher and infrastructure is well-established. However, as the negative effect of female illiteracy is strongest in these areas, priority should be given to providing financial support and targeted outreach to vulnerable groups with lower education levels. Central regions (such as Henan, Hubei, Hunan, Jiangxi, and Anhui provinces) can draw on the strategies used in the East to consolidate their existing advantages. These regions can also serve as a model for the West by expanding the eligibility of preferential HPV vaccination policies and exporting successful management experiences.

3.5 本研究的局限性

Furthermore, by utilizing behavioral incentives to translate high levels of knowledge into high vaccination rates, it is possible to ultimately improve HPV vaccine coverage through precise and localized strategies. Although this study employed various statistical methods to evaluate the relationships between multiple factors and HPV vaccine coverage, several limitations remain.

Advancing the elimination of cervical cancer.

Author Contributions: Yu-Tong Luo proposed the primary research objectives, performed data collection and organization, conducted statistical processing, created the figures and tables, drafted the initial manuscript, and was

responsible for revisions. Jing Li was responsible for quality control and review, overall oversight of the article, and project supervision.

Limitations: First, the accuracy and completeness of the data may be subject to certain limitations, and data from some provincial administrative regions may contain biases. Second, this study did not fully account for other potential factors influencing HPV vaccination, such as cultural customs and religious beliefs.

···vaccination impact. These factors may play a significant role across different provincial administrative regions and populations, and future research could further explore their underlying mechanisms. Third, although this study analyzed the impact of several macro-social factors on HPV vaccine coverage, it did not conduct an in-depth exploration of individual-level factors—such as personal health behaviors, vaccination intentions, and information acquisition channels—which may also play a critical role in vaccination decision-making. Fourth, the scope of this research was primarily focused at the provincial level. There may be significant intra-regional disparities within the same province that could substantially influence HPV vaccine coverage, which this study was unable to fully reveal. Fifth, the explanatory power and goodness-of-fit of the Geographically Weighted Regression (GWR) model varied across different provincial administrative regions, which may affect the accuracy and reliability of the research results. Therefore, subsequent plans involve introducing···

The authors declare no conflicts of interest.

Global Cancer Statistics and Trends

According to the latest data from GLOBOCAN 2022, cancer remains a significant global health challenge. Estimates indicate a substantial burden of disease, with incidence and mortality rates analyzed across 36 different cancer types in 185 countries [**?**]. These statistics underscore the critical need for continued research and targeted interventions to mitigate the impact of cancer worldwide.

In the specific context of China, recent reports from 2022 highlight the evolving landscape of cancer incidence and mortality [**?**]. The data reflects the unique epidemiological trends within the region, providing essential insights for public health planning and the development of localized treatment strategies. Understanding these patterns is vital for improving patient outcomes and optimizing resource allocation in the fight against cancer.

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Note: Figure translations are in progress. See original paper for figures.