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RESEARCH ARTICLE

How does air quality affect residents' life satisfaction? Evidence based on multiperiod follow-up survey data of 122 cities in China

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Abstract

Since entering the new era, China's socialist contradiction has been transformed into the contradiction between the people's growing need for a better life and the unbalanced and inadequate development. How to improve the quality of people's life through the improvement of air quality has become an important content restricting social development and a key problem to be solved. Based on the life satisfaction (LS) method, this study takes air quality into the individual utility function, and through matching China Health and Retirement Longitudinal Study (CHARLS), two phases of microindividual tracking data with 122 urban environmental quality data innovatively investigate the impact of air quality on residents' LS and its income substitution effect. The results show that air quality significantly reduces residents' LS, among which, different air pollutants and comprehensive air quality AQI have significant negative effects. And PM10 has the highest marginal effect on different LS evaluation, SO2 has the smallest marginal effect, and AQI marginal effect is close to PM10. In terms of group heterogeneity, NO2 and SO2 have group influence differences in age group, regional economic group, gender group, and family per capita income group. But PM10 and AQI do not show group influence heterogeneity, and air quality has significant negative effect on LS of different groups. In addition, the interaction between air quality and income level shows that air quality strengthens the difference of residents' LS caused by income level difference. According to the equilibrium condition of residents' individual utility function, the improvement of air quality by 1% is equivalent to the improvement of residents' LS by 23.4402% of income. Firstly, air quality has an important impact on residents' LS, and different air pollutants have different effects. Secondly, the impact of air quality on LS of different groups is heterogeneous and mainly diversified in age group, regional economic group, gender group, and family per capital income group. Finally, there is substitution effect between air quality and regional GDP growth and household income, which affects residents' LS. Thirdly, the conclusion shows that the improvement of air quality is difficult to be replaced by other ways. Good air quality can not only directly improve residents' LS, but also has economic effect.

Keywords Air quality · Life satisfaction (LS) · Air pollutants · Economic effect · Ordered logit model

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Highlights Air quality has an important impact on residents' life satisfaction, and different air pollutants have different effects.
The impact of air quality on life satisfaction of different groups is heterogeneous and mainly manifested in age group, regional economic group, gender group, and family per capita income group.
There is substitution effect between air quality and regional GDP growth and household income, which affects residents' life satisfaction.

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Introduction

Since entering the twenty-first century, China's social economy has achieved rapid development. By the end of 2020, China's per capita GDP has reached 72371 yuan.[1] The increasing improvement and promotion of the economic situation has further promoted the people's yearning for a better life, and the disharmonious development between man and nature has seriously threatened the health quality of residents. For example, according to the list of carcinogens published by the international agency for research on cancer of the World Health Organization in 2017, outdoor air pollution is a class of carcinogens because it is rich in particulate matter.[2]

The relationship between environmental quality and residents' life is investigated from the perspective of major social contradictions. Traditional studies pay more attention to the impact of environmental quality on residents' health, ignoring the analysis from the perspective of residents' yearning for a better life. From this perspective, we need to select LS or happiness including health quality as an agent, because these two indicators are more effective comprehensive reflection of the living conditions or residents' quality of life. Therefore, based on the existing law of environmental quality change, the research on the impact of air quality on residents' LS in the main body of environmental quality is to provide theoretical support for clarifying the internal logical relationship between air pollution control and improving residents' life quality. Therefore, it has important practical and theoretical significance.

Taking the ecological environment as the theme, we can find that the current research content is relatively rich. Among them, the literature on residents' quality of life from the perspective of air quality mainly focuses on the impact on residents' LS or happiness. As an important measure of social welfare, life satisfaction is a comprehensive reflection of residents' evaluation of the quality of life (Veenhoven 1999). In terms of the relationship between LS or well-being and socioeconomic growth, along with a country's socioeconomic growth, people's well-being or LS has a downward trend, which is a typical "Easterlin" paradox of unhappiness growth. Its core is that people's LS or well-being does not increase synchronously with the rapid economic growth (Easterlin 1974). However, from the perspective of early demand theory, socioeconomic development promotes the improvement of residents' quality of life (Liao et al. 2005) and does not show the higher LS characteristics of residents living in better areas than those living in poor areas (Lewis and Lyon 1986). The reason is that there are indirect effects of other substitutes (Lu 1999; Diener and Lucas 2000), such as personal socioeconomic or psychological factors characteristics (Thoits and Hewitt 2001; Liao et al. 2015).

On this basis, more and more scholars bring environmental quality into the study of happiness economics, or investigate the impact of residents' happiness, especially air quality from the perspective of environmental economics, and the importance of research is increasingly prominent (Ambrey et al. 2014). That is to say, under different disciplines, scholars' research conclusions on the impact of air quality on LS are also inconsistent. For example, from the perspective of environmental economics and happiness economics, scholars have investigated the influencing factors of residents' well-being respectively from the micro- and macroperspectives of gender, age, income, unemployment, and inflation (Morawetz et al. 1977; Clark and Oswald 1994). However, with the development of society, more and more scholars put environmental quality as a public good into the category of happiness economics, such as regional temperature, flood, and other environmental factors (Brereton et al. 2008; Luechinger and Raschky 2009; Levinson 2012). From the perspective of public management, LS is also an important embodiment of government credibility. For example, in environmental governance, LS is one of the important criteria for residents to evaluate the quality of government public service supply (Deichmann and Lall 2007; Graafland and Compen 2015; Chapman et al. 2019). Air pollution will not only reduce residents' LS, but also indirectly transfer to their trust or trust in the government satisfaction (Welsch 2006; Giovanis and Ozdamar 2016; Liang et al. 2018; Liu et al. 2020; Ke et al. 2021). Environmental governance is not only a potential public opinion reflection, but also an important guarantee of government credibility (Kestila-Kekkonen and Soderlund 2015).

No matter what kind of theory or discipline perspective is used to investigate the impact of environmental quality on LS, it is bound to stay in a certain logical framework. We also attempt to summarize the relevant conclusions of the existing research on the relationship between environmental quality and residents' quality of life and mainly summarize it into two parts from the perspective of air quality, namely, the "absolute deprivation effect" and "relative deprivation effect" caused by air quality on residents' life. (1) The "absolute deprivation effect" of air quality means that for all residents, in the case of poor or better air quality, the benefit or damage may

[1] http://www.mofcom.gov.cn/article/i/jyjl/l/202102/20210203038237.shtml. According to the preliminary statistics of China's GDP in 2020, the per capita GDP is calculated.

[2] The International Center for research on cancer under the World Health Organization (WHO) classifies carcinogens as follows: class I carcinogens refer to substances with sufficient evidence to prove their carcinogenicity, such as alcohol, formaldehyde, mustard gas, neutron radiation, radium and other radioactive elements, and air pollutants represented by asbestos, aflatoxin, and PM2.5; class II carcinogens refer to substances with certain evidence to prove their carcinogenicity animal carcinogenicity, but there is limited evidence to support the existence of human carcinogenic substances, such as lead and its compounds, polychlorinated biphenyls and DDT, naphthalene, and nitrobenzene; three types of carcinogens refer to the substances that lack sufficient evidence to prove human carcinogenicity and experimental animal carcinogenicity but have sufficient theoretical support, such as aniline, phthalate plasticizer, and sudan red.

occur. Firstly, air pollution makes the health level of residents decrease and the prevalence rate increase and reduces the transmission of health to LS (Bowatte et al. 2017; Munzel et al. 2018; Toledo-Corral et al. 2018; Guo et al. 2019); second, air pollution will also reduce residents' choice of going out and cause inconvenience to their lives (Ferreira and Moro 2010). For example, when haze occurs across the country, to a certain extent, it will cause residents to reduce going out for sports or outdoor activities (Villeneuve et al. 2012; Tamosiunas et al. 2014). (2). The "relative deprivation effect" of air quality means that compared with the high-income group, the low-income group not only suffers from income weakness, but also suffers more from air pollution, which further strengthens their income weakness. Whether there are differences in the relationship or sensitivity between LS and air quality among different income groups is another issue of this study. In theory, when high-income groups are faced with air pollution, they will choose more alternative behaviors, such as choosing immigration or using high-tech products to reduce the impact of air pollution on themselves (Price and Feldmeyer 2012). Thus forming an inequality phenomenon, that is, high-income groups reduce the impact of air pollution on themselves through high-income alternative means, while low-income groups reduce the impact of air pollution on themselves because of income restriction; it is difficult to have alternative choices (Gordon et al. 2014).

Combined with the existing research, we can find that scholars' research results on the relationship between air quality and residents' LS are relatively rich, and more of them focus on the analysis from the perspective of environmental economics or happiness economics. However, there are still some deficiencies in the current research. First, the research on China is mostly focused on early data analysis. Since 2017, the central government has implemented policy adjustments. Comrade Xi Jinping clearly put forward the important idea of "two mountains" in the nineteen major reports of the party, which has great influence on the environmental improvement in recent years. Therefore, the analysis of data before and after 2017 is very important. It should be of practical significance. Secondly, in the existing studies, scholars focus on the air quality research from a single dimension, such as the traditional air pollution index (API) analysis or the air quality index (AQI). The latter can be used as a comprehensive index for robustness test and can comprehensively reflect the LS effect of air quality. Based on this, we mainly attempt to make a breakthrough from the following two points: Firstly, based on the tracking data of China Health and pension tracking survey (CHARLS) database in 2015 and 2018, this study attempts to explore the evolution trend of the relationship between air quality improvement and residents' LS under the influence of the new environmental policy, analyze its internal logical relationship, and reveal the importance of the impact of external environment on residents' life. Secondly, on the basis of API, we discuss the impact of major pollutants on residents' LS and conduct a robustness test with AQI to investigate the heterogeneity of residents' LS under the influence of different pollutants, as well as the income substitution effect of AQI, so as to enrich the research perspective of residents' LS and break through the existing research conclusion on limitations.

Methods

Theoretical derivation

Combing the current studies, it can be found that most of the studies use utility function to analyze the impact of air quality on residents' quality of life, and the two main types are revealed: preference method (Huang et al. 2012; Gonzalez et al. 2013) and stated preference method (Istamto et al. 2014; Rizzi et al. 2014). However, due to the problems of hypothetical bias, information bias, and strategic bias, the above two methods have some shortcomings in estimation. The life satisfaction approach (LSA) combines subjective and objective data and only needs a subjective indicator of LS, without the need to examine environmental quality preferences and other issues, which can effectively avoid the defects of the former two methods. We also attempt to use this method to investigate the impact of air quality on residents' LS. LSA is based on the maximization of individual utility. Assuming that individual utility is composed of income, market goods or services, environmental goods or services, and self-preference, the individual utility function can be set as follows:

$$U_{ijt} = u(x, q, y, s, \varepsilon)_{ijt} \tag{1}$$

In Eq. (1), $U_{ijt}$is the utility of individual$i$in$j$city in year$t$, where$x$on the right is the market commodity, and $q$refers to the goods in the nonmarket environment. We focus on the air quality in the environmental quality, and $y$refers to the individual income or the regional per capita GDP, $s$represents individual preferences and other socioeconomic characteristics, and εrepresents other random error terms. Theoretically, there is a positive correlation between the individual utility u and its income y and nonmarket goods q, so the individual utility can be derived separately, and the following conditions are satisfied:

$$\begin{aligned} &\partial u(x, q, y, s, \varepsilon)_{ijt}/\partial q_{ijt} > 0, \\ &\partial u(x, q, y, s, \varepsilon)_{ijt}/\partial y_{ijt} > 0 \end{aligned} \tag{2}$$

According to Eq. (2), and assuming that market commodity$x$, individual preference, and other socioeconomic characteristics$s$can be kept unchanged, the individual utility function is adjusted as follows:

$$\Delta u_{ijt} = \left(\partial u_{ijt}/\partial y_{ijt}\right)\Delta y_{ijt} + \left(\partial u_{ijt}/\partial q_{ijt}\right)\Delta q_{ijt} \tag{3}$$

Assuming that the individual utility is maximized, then$\Delta u_{ijt} = 0$can be obtained, and Eq. (4) can be deduced, that is,

$$\left(\partial u_{ijt}/\partial y_{ijt}\right)\Delta y_{ijt} = -\left(\partial u_{ijt}/\partial q_{ijt}\right)\Delta q_{ijt} \tag{4}$$

Equation (4) indicates that the increase of utility brought by the increase of individual income should be equal to the decrease of utility caused by the decrease of air quality, so that the air quality price can be derived, that is,

$$\Delta y_{ijt}/\Delta q_{ijt} = -\left(\partial u_{ijt}/\partial q_{ijt}\right)/\left(\partial u_{ijt}/\partial y_{ijt}\right) \tag{5}$$

Equation (5) is the pricing formula of air quality, whose core is to price the marginal effect of individual utility through income and air quality, which is also the core of LSA. Equation (5) can also be expressed as the substitution relationship between air quality and individual income when individual LS remains unchanged. That is to say, under the condition that the individual LS remains unchanged, the air quality reduction effect brought by increasing the income of one unit can reflect the income effect of air quality.

Empirical model design

The results show that residents' LS is affected by individual social demographic characteristics and regional macroenvironmental characteristics. Combined with the previous theoretical model analysis, we further construct the corresponding empirical test model. Considering that the core explanatory variable of this study is residents' LS, because residents' LS has classification characteristics, that is, there are classification and ranking characteristics on indicators, the traditional OLS estimation will cause the result error, so the ordered panel logit model is selected for test:

$$LS_{ijt} = \alpha \ln \mathrm{Air}_{\mathrm{jt}} + \beta y_{ijt} + \kappa X_i + \chi H_j + \varphi S_{ijt} + \lambda_i + \delta_j + \eta_t + \varepsilon_{ijt} \tag{6}$$

In Eq. (6),LS_{ijt}represents the residents' LS of*j*city individual*i*in year*t*, which is the core explanatory variable of the study. TheAir_{jt}on the right of Eq. (6) represents the air quality of city*j*in year*t*, which is the core explanatory variable of this study. In this study, SO2, NO2, and PM10 in API are selected as proxy variables, and AQI index is selected for robustness test. In data processing, in order to avoid the influence of nondimensional numerical value, we carry out logarithmic processing to test. And$y_{ijt}$is the variable of individual income;$X_i$is the social and demographic characteristics of individual *i*, such as gender, age, and widowhood;$H_j$is the variable of urban environmental characteristics of*j*, including regional financial expenditure, annual rainfall, and annual sunshine duration. Because the panel ologit model only provides random effect test results, in order to ensure the reliability of the estimation results, the individual effect, regional effect, and year effect are controlled in the model at the same time, that isλ_i,δ_j, and $\eta_t$in Eq. (6),andε_{ijt}represents random error term. Based on the previous analysis, the marginal substitution rate of air quality and residents' income can be expressed as Eq. (7) according to Eq. (5).$|\alpha/\beta|$is the substitution rate between them. This study focuses on the marginal substitution rate between air quality and regional per capita GDP, that is, to do correlation analysis of macroindicators, focusing on the economic effect of air quality. It is shown in formula (7):

$$MRS|_{Air} = -\frac{\frac{\partial LS}{\partial Air}}{\frac{\partial LS}{\partial y}} = -\frac{\alpha}{\beta} \times \frac{y}{Air} \tag{7}$$

Key variables and data sources

Individual data

The individual microdata of this study is selected from the tracking survey data of China Health and Retirement Longitudinal Study (CHARLS) in 2015 and 2018. CHARLS survey database covers 28 provinces in China[3]. The final sample number of the study is obtained after eliminating the missing value and invalid value of the sample, including 18,989 individual data in 2015 and 17,895 in 2018. Based on the comprehensiveness of individual information data in CHARLS database, combined with the data matching of air pollutants in 122 regions, a two-stage panel data model is constructed. By controlling the individual and time effects, as well as the social characteristics of the individual population and the macrocharacteristics of the city, the reliability and accuracy of the estimation results of the effect of air quality on individual LS can be improved.

The core explanatory variable of this study is residents' LS. According to the question "overall, are you satisfied with your life" in the questionnaire, combined with the option "extremely satisfied, very satisfied, relatively satisfied, not very satisfied, and not satisfied at all," the corresponding assignment is made. The assignment of "extremely satisfied" is 5, "very satisfied" is 4, "relatively satisfied" is 3, "not very satisfied" is 2, and "not at all satisfied" is 1, thus forming the ranking characteristics of satisfaction to comprehensively reflect the living conditions of residents.

Through data processing, the statistics of residents' LS are shown in Table 1. It can be seen from Table 1 that from 2015 to 2018, the overall situation of residents' LS tends to be better. For example, compared with 2015, the number of residents who are relatively satisfied, very satisfied, and

[3] Hainan province, Tibet autonomous pegion, and Ningxia autonomous region were not included in the sample.

extremely satisfied in Table 1 has increased in 2018, and its proportion in the total population has increased from 57.13 to 65.72%. Meanwhile, the evaluation probability of residents' low LS has decreased from 42.87% in 2015 to 34.28% in 2018.

Air quality data

The main indicators reflecting air quality are emission of pollutants in exhaust gas; concentration detection of several air pollutants, such as SO2, NO2, and PM10; and annual air pollution index (API) and annual air quality index (AQI). Among them, the main pollutants in the exhaust gas are mainly industrial emissions, and the comprehensive reflection of air quality is limited. AQI is based on the original API, adding fine particulate matter (PM2.5), ozone (O3), and carbon monoxide (CO) indicators, which has a comprehensive advantage. And its release frequency is once an hour, so it has a good advantage to select the annual average value of AQI to investigate its impact on residents' LS. In addition, considering the universal impact of API indicators, we still select API indicator for benchmark analysis and separately bring SO2, NO2, and PM10 into the model for testing, while AQI is used as a substitute indicator for robustness testing.

Control variables

In addition to air quality, the main indicators affecting residents' LS also include social development characteristics, such as individual social demographic characteristics and macroenvironment characteristics of the city. Therefore, it is necessary to introduce the model into control variables, and we will control the individual demographic characteristics from family income, gender, age, registered residence, widowed spouse, and education level and from the regional fiscal expenditure, per capita GDP, population density, sunshine duration, rainfall, and other aspects to control the regional macroenvironmental characteristics. The descriptive statistics of specific variables are shown in Table 2.

It can be seen from Table 2 that the coefficients of variation of residents' LS in 2015 and 2018 are 0.301 and 0.292, respectively, with a small degree of dispersion, and mainly with relatively satisfied and not very satisfied. The coefficients of variation of SO2, NO2, and PM10 concentrations in 2015 and 2018 were 0.652 and 0.651, 0.355 and 0.406, and 0.434 and 0.449, respectively, indicating that the dispersion degree of NO2 and PM10 was similar. And the dispersion degree of SO2 was larger. The dimensionless statistical values of AQI in 2015 and 2018 were 85.76 and 72.14, respectively, indicating that the air quality improved significantly in 2018. The definitions and statistical results of other variables are shown in Table 2.

Results

Benchmark regression results

Firstly, we investigate the impact of air quality on residents' LS and test the effects of different pollutant concentrations and comprehensive air quality index (AQI). The specific results are shown in Table 3.It can be seen from model (1) to model (3) in Table 3 that different pollutants have significant negative effects on residents' LS when the concentration of air pollutants is taken as the core. That is to say, the higher the concentration of NO2, SO2, and PM10 in the air, the lower the level of residents' LS, showing a typical environmental effect. Table 3 model (4) is the test result with the air quality composite index AQI as the core explanatory variable, which further confirms the negative effect of air quality on residents' LS. That is to say, from the perspective of the overall air quality measurement index, the worse the overall air quality, the lower the residents' LS, which demonstrates the reliability of the test results. And the results of this study are consistent with the existing studies. For example, the study of Di et al. (2020) shows that the improvement of air quality can reduce the depression and anxiety of rural residents.

In terms of control variables, logarithm of sunshine duration, logarithm of per capita GDP, logarithm of average temperature, and relative humidity have significant effects on residents' LS, and logarithm of sunshine duration and logarithm of per capita GDP have negative effects. That is to say, when

Table 1 Distribution probability statistics of residents' life satisfaction

Life satisfaction	2015		2018	
	Number of samples	Frequency (%)	Number of samples	Frequency (%)
Not at all satisfied	1289	0.0679	911	0.0509
Not very satisfied	6851	0.3608	5223	0.2919
Relatively satisfied	9244	0.4868	9683	0.5411
Very satisfied	1279	0.0674	1517	0.0848
Extremely satisfied	326	0.0172	561	0.0313

Table 2 Descriptive statistics of variables

Variable	Definition	2015 (18,989)		2018 (11,7895)	
		Mean	S.D.	Mean	S.D.
Life satisfaction	1 ~ 5 respectively indicate that the level of satisfaction is getting higher and higher	2.605	0.783	2.754	0.803
SO_2	SO2 content in air, unit: μg /m3	27.53	17.96	16.26	10.58
NO_2	NO_2 content in air, unit: μg /m3	32.74	11.62	39.23	15.93
PM_{10}	PM_{10} content in air, unit: μg /m3	94.38	40.94	89.74	40.32
AQI	Dimensionless air quality, the greater the value, the worse	85.76	25.79	72.14	16.55
Fiscal expenditure	The total annual fiscal expenditure of the region, unit: 100 million yuan/year	544.9	729.6	688.0	1030
Sunshine duration	Annual total sunshine duration, unit: hour/year	1814	469.0	1903	354.4
Rainfall	Annual total rainfall, unit: mm/year	1067	624.8	997.3	441.2
Per capita GDP	Annual regional GDP to population ratio, unit: yuan/person	49467	34418	56468	35992
Population density	Annual area to population ratio, unit: per person per square meter	490.1	479.4	492.6	473.1
Average temperature	Annual average temperature, unit: centigrade	15.24	3.867	15.08	3.926
GDP growth	GDP growth compared with the previous year	8.078	2.081	7.054	1.823
Green space coverage	Ratio of green area to total area in built up area, unit: %	39.54	9.130	39.96	5.022
Relative humidity	Percentage of water vapor pressure in air to saturated vapor pressure at the same temperature	64.65	12.39	65.03	10.64
Household register	Urban residence =1, rural residence =0	0.401	0.490	0.405	0.491
Income	Per capita household income, yuan/year	4084.9	12,222	4704.91	8627
Widowed	Widowed = 1, no = 0	0.103	0.304	0.125	0.330
Age	The actual age of the individual in the survey	59.14	10.32	58.74	10.32
Gender	Male = 1, female = 0	0.478	0.500	0.474	0.499
Education	1-11 means higher and higher level of education	3.390	1.001	3.477	1.935

Note: The number of samples is in brackets

the annual sunshine duration and per capita GDP increase, the residents' LS is relatively low. The reason is that the higher sunshine duration will enhance the residents' subjective sensitivity to air quality, such as directly feeling the poor air quality and producing negative psychology. And the higher per capita GDP will further enhance the residents' pursuit of high air quality, which is the internal mechanism of regional economic development and also an important part of residents' social life. The logarithm of average temperature and relative humidity are mainly positive; that is, the higher the average temperature and relative humidity are, the higher the residents' LS will be. In terms of individual demographic characteristics, registered residence, gender, and age have a significant negative effect on the LS of residents. If the registered residence is urban and gender is male and the age is higher, the LS of residents will be lower; otherwise, the opposite is true. Whether widowed and education level have a significant positive effect on residents' LS, that is, compared with the residents without widowed or with low education level, the residents with widowed or with high education level have significantly higher LS.

From the above results, air quality has a significant impact on residents' LS. In addition, from the perspective of the marginal economic value of the impact of air quality on residents' LS, in order to keep residents' LS unchanged, when SO2, NO2, PM10, and AQI increase by 1 percentage point, the decrease of residents' LS needs to be compensated by the growth of 0.5743, 3.1163, 3.3957, and 2.5895 percentage points of regional per capita GDP, respectively. At the same time, we can also examine the marginal substitution relationship between household per capita income and residents' LS, that is, the marginal income value of air quality.

Marginal effect analysis

We further estimated the marginal effect of air quality on residents' LS, and the results are shown in Table 4. Considering that logit model parameters only give limited information about direction and significance, we further estimate the marginal effect of air quality on the basis of Table 3.That is, when all explanatory variables are at the mean value, the influence of exogenous explanatory variables on the explained variables can be expressed as Eq. (8),that is,

$$\frac{\partial prob(LS = i/Air)}{\partial Air}\Big|_{Air=\overline{Air}}(i = 1, 2, 3, 4, 5) \quad (8)$$

Table 3 Impact of air quality on residents' life satisfaction: benchmark regression results

	(1)	(2)	(3)	(4)
$lnSO_2$	−0.0788** (0.0369)			
$lnNO_2$		−0.2493*** (0.052)		
$lnPM_{10}$			−0.3776*** (0.052)	
lnAQI				−0.3343*** (0.0772)
Fiscal expenditure	0.0114 (0.0271)	0.0291 (0.0269)	0.0090 (0.0269)	0.0150 (0.0268)
Sunshine duration	−0.3188*** (0.088)	−0.3189*** (0.087)	−0.3550*** (0.087)	−0.3335*** (0.0873)
Rainfall	0.1031 (0.0633)	0.0669 (0.0628)	−0.0012 (0.0633)	0.1016 (0.0623)
Per capita GDP	−0.1372*** (0.033)	−0.0800** (0.0356)	−0.1112*** (0.033)	−0.1291*** (0.0333)
Population density	−0.0255 (0.0222)	0.0087 (0.0237)	0.0469* (0.0247)	−0.0004 (0.0234)
Average temperature	0.1584* (0.0932)	0.2073** (0.0934)	0.1497 (0.0931)	0.1864** (0.0934)
GDP growth	−0.0001 (0.0097)	0.0003 (0.0096)	0.0102 (0.0097)	0.0038 (0.0096)
Green space coverage	−0.0032 (0.0025)	−0.0025 (0.0025)	−0.0033 (0.0025)	−0.0036 (0.0025)
Relative humidity	0.0076** (0.0030)	0.0061** (0.0030)	0.0044 (0.0030)	0.0054* (0.0031)
Household register	−0.0586 (0.0364)	−0.0663* (0.0364)	−0.0750** (0.0364)	−0.0731** (0.0364)
Income	0.0500 (0.0396)	0.0492 (0.0396)	0.0516 (0.0395)	0.0461 (0.0396)
If widowed	0.2535*** (0.0671)	0.2518*** (0.0670)	0.2494*** (0.0669)	0.2516*** (0.0671)
Gender	−0.1503*** (0.035)	−0.1509*** (0.035)	−0.1502*** (0.035)	−0.1491*** (0.0349)
Age	−0.0156*** (0.002)	−0.0154*** (0.002)	−0.0155*** (0.002)	−0.0155*** (0.0019)
Education	0.0426*** (0.0104)	0.0432*** (0.0104)	0.0427*** (0.0103)	0.0426*** (0.0104)
Individual / Year	Yes	Yes	Yes	Yes
$\lvert\alpha/\beta\rvert$	0.5743	3.1163	3.3957	2.5895
sigma2_u	2.0234*** (0.1281)	2.0151*** (0.1278)	2.0030*** (0.1277)	2.0164*** (0.1281)
Pseudo log likelihood	−28405.888	−28396.788	−28380.57	−28398.727
Observations	25247	25247	25247	25247

Note: The standard errors are in brackets, *** p<0.01, ** p<0.05, * p<0.1. The model controls both year effect and individual effect to control the influence of unobservable factors, the same below

Table 4 reports the marginal effect of air quality on residents' LS. From the perspective of marginal effect of air quality, the concentrations of pollutants in air quality significantly increase the probability that residents are not satisfied with their lives at all. On the whole, the positive marginal effect of not being satisfied with residents is the highest, and the marginal effect of PM10 concentration is the highest. The research of Liang et al. (2018) also shows that air pollution and green coverage are significantly negatively and positively correlated with LS perspective. When the concentration of PM10 increased by 1 unit, the probability of residents not satisfied with their life at all increased by 1.73% and 4.64%, while the marginal effect of NO2 ranked second, and the marginal effect of SO2 was the smallest. From the perspective of the comprehensive air quality AQI index, when the AQI is increased by one unit, the probability of residents not being satisfied at all and not being very satisfied with their life is increased by 1.53% and 4.11%, respectively. In terms of

Table 4 Marginal effect of air quality on residents' life satisfaction

Life satisfaction	lnSO2	lnNO2	lnPM10	lnAQI
Not at all satisfied	0.0036** (0.0017)	0.0114*** (0.0024)	0.0173*** (0.0024)	0.0153*** (0.0035)
Not very satisfied	0.0097** (0.0045)	0.0307*** (0.0065)	0.0464*** (0.0065)	0.0411*** (0.0095)
Relatively satisfied	−0.0075** (0.0035)	−0.0239*** (0.0050)	−0.0362** (0.0050)	−0.0320*** (0.0074)
Very satisfied	−0.0040** (0.0019)	−0.0128*** (0.0027)	−0.0194** (0.0027)	−0.0172*** (0.0040)
Extremely satisfied	−0.0017** (0.0008)	−0.0055*** (0.0012)	−0.0083** (0.0012)	−0.0073*** (0.0017)

Note: The standard error is in brackets, *** p<0.01, ** p<0.05, * p<0.1. Control variable results are not listed

negative effects, the concentrations of pollutants in air quality significantly reduce the probability of residents' relatively satisfied, very satisfied, and extremely satisfied with life. On the whole, the marginal reduction effect of residents' relatively satisfied is the highest, and the marginal reduction effect of residents' extremely satisfied should be the lowest. From the difference of pollutant concentration, the marginal effect of PM10 is still the highest. When the concentration increases by 1 unit, the probability of residents' satisfaction is 3.62%, 1.94%, and 0.83%, respectively. From the perspective of AQI marginal effect, the above results are still stable. When the AQI value increased by one unit, the probability of relatively satisfied, very satisfied, and extremely satisfied decreased by 3.20%, 1.72%, and 0.73%, respectively.

Analysis of group heterogeneity

In order to investigate the heterogeneity of the impact of air quality on the evaluation of LS of different groups, we further analyze from the perspectives of age, regional economy (GDP), gender, and per capita household income, and the results are shown in Table 5.

In terms of age group, we examine the impact of air quality on the aging population and nonaging population, respectively, that is, taking 60 years old as the dividing point for heterogeneity. The results show that SO2 has a significant negative impact on the LS of the nonelderly population under 60 years old, but has no significant impact on the LS of the elderly population over 60 years old. However, there is no significant age difference in the impact of other pollutants on residents' LS, and there is a significant negative impact on different age groups. Under the AQI index of air quality, this conclusion is still robust; that is, the age heterogeneity of the population is not obvious.

In terms of regional economic groups, we select the regional economic aggregate as the grouping standard; that is, the regional GDP lower than the average GDP is the low economic group, while the regional GDP higher than the average GDP is the high economic group. The results show that SO2 and NO2 in air pollutants have obvious regional economic heterogeneity. SO2 only has a significant impact on residents' LS in high economic group, NO2 only has a significant impact on residents' LS in low economic group, while PM10 has no significant regional economic heterogeneity on residents' LS. In addition, in terms of air quality AQI index, different regional economic characteristics show a significant negative effect of AQI index; that is, AQI index has no significant regional economic heterogeneity.

In terms of gender group, compared with male residents, SO2 in air pollutants has more significant impact on female residents' LS, while NO2 and PM10 have no significant gender difference. The overall air quality index (AQI) does not show significant gender differences, and it has a significant

Table 5 Heterogeneity of air quality influencing residents' life satisfaction

Grouping	Indicators	$\ln SO_2$	$\ln NO_2$	$\ln PM_{10}$	lnAQI	Observations
Age group	Under 60	−0.1091** (0.0494)	−0.1791** (0.0696)	−0.3579*** (0.0717)	−0.3469*** (0.1046)	14081
	Over 60 years old	−0.0519 (0.0555)	−0.3227*** (0.0796)	−0.4075*** (0.0761)	−0.3444*** (0.1149)	11166
Regional economic group	Low GDP group	−0.0100 (0.0422)	−0.2276*** (0.0565)	−0.3701*** (0.0633)	−0.2862*** (0.0969)	18067
	High GDP group	−0.2739*** (0.0958)	−0.0244 (0.1770)	−0.4807*** (0.1285)	−0.4134** (0.1650)	7180
Gender group	Male	−0.0345 (0.0546)	−0.2278*** (0.0770)	−0.3263*** (0.0767)	−0.4087*** (0.1120)	11618
	Female	−0.3675*** (0.0440)	−0.2624*** (0.0715)	−0.4187*** (0.0715)	−0.2801*** (0.1070)	13629
Per capita household income group	Low-income group	−0.0575 (0.0376)	−0.2387*** (0.0530)	−0.3494*** (0.0529)	−0.3271*** (0.0792)	24004
	High-income group	−0.4202*** (0.1270)	−0.1186 (0.2361)	−0.8154*** (0.1978)	−0.4776** (0.2267)	1243

Note: The standard errors are in brackets, *** p<0.01, ** p<0.05, * p<0.1. Control variable results are not listed

negative impact on the LS of both male and female residents. That is to say, when the AQI index increases, the LS of both male and female residents will decrease significantly.

In terms of the per capita income group of the family, the residents in the sample are defined as high-income groups and those lower than average income are defined as low-income groups. The results show that when the household income group is used as the heterogeneity criterion, it is similar to the group heterogeneity based on the regional economy. That is to say, the group heterogeneity of family per capita income group is mainly manifested in the significant impact of SO2 on high-income group residents and the significant impact of NO2 on low-income group residents. However, there is no significant difference in group income heterogeneity under other pollutants or air quality indicators.

Analysis of interaction between air quality and severe disease rate

Income is one of the most important factors in the individual social demographic characteristics that affect residents' LS. This study also analyzes the important substitution effect of regional per capita GDP on air quality. As a more direct reflection of individual economic situation, the effectiveness of per capita household income will be higher. Therefore, we will introduce the interaction between household per capita income and air quality in this part to investigate whether the household per capita income level plays a corresponding regulatory role in the relationship between air quality and residents' LS when maintaining the residents' LS. The results are shown in Table 6. In order to investigate the hierarchical characteristics of the impact of family income, we divide the family per capita income into different levels: the high-income group is defined as 1, and the low-income group is defined as 0.The results in Table 6 show that when the interaction between household income level and air quality is introduced, the impact of air pollutant concentration on residents' LS is still significant, and the interaction is only significant in model (2) and model (3). That is, when the concentration of NO2 and PM10 in the air is fixed, the promotion of income level can effectively reduce the negative effect of air quality on residents' LS. Compared with low-income residents, in the same air environment, high-income residents can use better living security measures to reduce the harm of air quality to their body, such as choosing a more suitable living environment and using higher medical security measures. Similarly, in the case of a certain income level, the deterioration of air quality reduces the LS of residents of all income levels.

The results of the above interaction items show that air quality strengthens the difference of LS caused by the income difference of residents. And the positive promotion of the interaction items of income grade and air quality of NO2 and PM10 concentration is the main factor. The core reason is that with the increase of air pollutants, the impact on the health of low-income residents is greater, which will not only increase the health cost of their work, but also cause higher direct medical consumption, thus further transmitting to their evaluation of LS.

Discussions

Considering the problems of self-selection error and missing variables in sample selection, we select control sample and two-way fixed effect to deal with the above problems that may cause estimation error in further analysis.

Error processing of sample self-selection estimation

In the aspect of sample self-selection, due to the phenomenon of environmental migration, when residents have better

Table 6 Interaction between air quality and income level on residents' life satisfaction

Variable	(1)	(2)	(3)	(4)
$lnSO_2$	−0.0767** (0.0346)			
$lnNO_2$		−0.2064*** (0.0481)		
$lnPM_{10}$			−0.3156*** (0.0481)	
lnAQI				−0.3265*** (0.074)
Income level	0.1449 (0.1613)	−0.1511 (0.2453)	−0.2090 (0.2918)	−0.4113 (0.4492)
Income level×$lnSO_2$/Income level×$lnNO_2$/Income level×$lnPM_{10}$/Income level×lnAQI	0.0422 (0.0489)	0.1247* (0.0697)	0.1093* (0.0642)	0.1563 (0.1010)
Individual/year	Yes	Yes	Yes	Yes
/sigma2_u	2.0168*** (0.0853)	2.0110*** (0.0851)	2.0022*** (0.0850)	2.0112*** (0.0852)
Pseudo log likelihood	−38867.866	−38860.833	−38847.415	−38860.38
Observations	25247	25247	25247	25247

Note: The standard errors are in brackets, *** p<0.01, ** p<0.05, * p<0.1. Control variable results are not listed

Table 7 Impact of air quality on life satisfaction of permanent residents

Variable	(1)	(2)	(3)	(4)
$lnSO_2$	−0.0831** (0.0379)			
$lnNO_2$		−0.1806*** (0.0597)		
$lnPM_{10}$			−0.2552*** (0.0536)	
lnAQI				−0.3179*** (0.0792)
Ln GDP per capita	−0.1306*** (0.0340)	0.0308 (0.0400)	−0.0720** (0.0364)	−0.1228*** (0.0340)
Individual/year	Yes	Yes	Yes	Yes
/sigma2_u	2.0363*** (0.1346)	2.0363*** (0.1346)	2.0247*** (0.1341)	2.0283*** (0.1344)
Pseudo log-likelihood	−27209.211	−27209.211	−27200.214	−27203.528
Observations	24186	24186	24186	24186

Note: The standard errors are in brackets, *** p<0.01, ** p<0.05, * p<0.1. Control variable results are not listed

economic conditions, they selectively migrate to low air pollution areas in order to avoid the decrease of health level caused by poor air quality, resulting in a significant negative impact of air quality on residents' LS. Therefore, based on the estimation error of this hypothesis, we select control samples to process. In order to reduce the estimation error caused by environmental migration, in the sample processing, the subsample test is carried out for the objects whose residence location and type have not changed. The results are shown in Table 7. The results show that SO2 has a significant negative impact on residents' LS at the level of 5%, and NO2, PM10 concentration, and AQI index have a significant negative impact on residents' LS at the level of 1%, which indicates that the research conclusion of the impact of air quality on residents' LS is robust.

Missing variable handling

Although the previous analysis synchronously controlled the corresponding individual sociodemographic characteristics and regional environmental characteristics variables, there are still potential missing variables, resulting in the bias of the estimation results. Therefore, in order to solve this problem, we first use the two-way fixed effect model to overcome the endogenous problem caused by missing variables. We take the classified variables as continuous variables and use the method of linear two-way fixed effect model estimation. At the same time, we also try to use this method to deal with the panel two-way fixed effect; that is, the residents' LS is regarded as a continuous variable, and the specific test results are shown in Table 8. It can be seen from Table 8 that compared with the benchmark model, air quality still has a significant negative impact on residents' LS, indicating that the previous research conclusion is robust.

Secondly, the instrumental variable method is used to deal with the missing variables. Here we mainly choose the ordered probit tool variable method for processing. As for the choice of instrumental variables, considering that the abundance of regional mineral resources is often used as the instrumental variable of air quality in some studies, and the

Table 8 Impact of air quality on residents' life satisfaction: based on fixed effect

Variable	(1)	(2)	(3)	(4)
$lnSO_2$	−0.0978*** (0.0195)			
$lnNO_2$		−0.0849** (0.0350)		
$lnPM_{10}$			−0.0746* (0.0438)	
lnAQI				−0.2419*** (0.0526)
Ln GDP per capita	0.2306*** (0.0443)	0.2506*** (0.0449)	0.2736*** (0.0434)	0.2228*** (0.0450)
Individual/year	Yes	Yes	Yes	Yes
sigma2_u	−1.0640 (1.0128)	−2.4868*** (0.9613)	−2.4268** (0.9803)	−0.7127 (1.0554)
F test	10.61	9.30	9.10	10.34
R^2	0.0237	0.0209	0.0204	0.0231
Observations	25247	25247	25247	25247

Note: The standard errors are in brackets, *** p<0.01, ** p<0.05, * p<0.1. Control variable results are not listed

Table 9 Estimation results of IV ordered probit model

Variable	(1)		(2)		(3)		(4)	
	First stage (lnSO2)	Second stage (LS)	First stage (lnNO2)	Second stage (LS)	First stage (lnPM10)	Second stage (LS)	First stage (lnAQI)	Second stage (LS)
Regional-mineral-resources endowment	18.0074*** (0.3361)		6.4223*** (0.2497)		7.8821*** (0.2522)		1.8217*** (0.1610)	
$lnSO_2$		−0.1637*** (0.0521)						
$lnNO_2$				−0.2461* (0.1431)				
$lnPM_{10}$						−0.3356** * (0.1178)		
lnAQI								−1.0970** (0.4722)
Ln GDP per capita		−0.059*** (0.014)		−0.046*** (0.015)		−0.0429*** (0.014)		−0.0468** * (0.014)
Individual/year		Yes		Yes		Yes		Yes
$\lvert\alpha/\beta\rvert$		2.7746		5.3500		7.8228		23.4402
First stage F value	2870.47		661.23		976.54		128.13	
R^2	0.0736		0.0180		0.0263		0.0035	
Observations	25247	25247	25247	25247	25247	25247	25247	25247

Note: The standard errors are in brackets, *** p<0.01, ** p<0.05, * p<0.1. Control variable results are not listed

proportion of regional mining industry employees in the total population is also used as the instrumental variable, we select the second measure, that is, the proportion of mining employees in the total population as the proxy variable of regional mineral resources endowment, and estimate it by using the two-stage method of IV ordered probit model. The results are shown in Table 9. From the first stage test results of model (1) to model (3) in Table 9, it can be seen that the mineral resource endowment of instrumental variable area has a significant positive effect on the air quality of core explanatory variable, and the F value in the first stage is significantly greater than 10, indicating that there is no weak instrumental variable problem. That is, the instrumental variable selection is effective. The second stage results of model (1) to model (3) in Table 9 show that, compared with the benchmark model, the impact of air quality on residents' LS is still significant after the treatment of instrumental variables, indicating that the results are robust. In addition, it can be seen from the model (4) in Table 9 that in order to keep the residents' LS unchanged, the decrease of residents' LS caused by every 1% increase in AQI index needs 23.4402% increase in regional GDP to make up for it. That is to say, the improvement of residents' LS caused by 1% air quality improvement is equivalent to the improvement of residents' LS caused by 23.4402% regional GDP improvement.

Conclusions

This study uses the tracking data of 2015 and 2018 from CHARLS database to construct panel data to empirically investigate the impact of air quality on residents' LS and its marginal effect. The results show that, first of all, air quality has a significant impact on residents' LS, and both the main pollutants and the overall air quality have a significant negative impact. Secondly, in terms of marginal effect, PM10 has the highest marginal effect on residents' LS, followed by NO2 and SO2. In the same impact effect, air quality has a significant positive impact on the evaluation of residents who are not satisfied and not very satisfied at all, and the marginal effect on residents' dissatisfaction is higher. And the impact of air quality on residents' LS is significantly negative, and the marginal negative effect on residents' LS is the highest. The above results are still robust under the overall AQI. Furthermore, the results show that SO2 has a significantly higher impact on residents under 60 years old, high GDP group residents, female group residents and high-income group residents, while NO2 has a significantly higher impact on low GDP group and low-income group residents. There is no significant group heterogeneity of other pollutants and comprehensive air quality AQI, and they all show a significant negative effect on LS of different groups. The results of controlling the interaction between air quality and residents' income level show that the improvement of income level weakens the impact of air quality on residents' LS. Finally, after dealing with the problem of sample self-selection and missing variables, the impact of air quality on residents' LS is robust. Through the research results, we can draw the following conclusions: firstly, air quality has an important impact on residents' LS, and different air pollutants have different effects. Secondly, the impact of air quality on LS of different groups is heterogeneous and mainly diversified in age group, regional economic group, gender group, and family per capital income group. Finally, there is substitution effect between air quality and regional GDP growth and household income, which effects residents' LS.

Combined with the research conclusions, the relevant policy implications are as follows: first, with the rapid development of social economy, in order to effectively alleviate the contradiction between "people's growing needs for a better life and unbalanced and inadequate development," the demand for "environment-friendly" social and economic development is increasingly strong, which should consider not only the short-term GDP development, but also the basic quality of life of local residents. In particular, it should reflect the LS or well-being of the residents' overall living standard evaluation and also take into account the heterogeneity of different groups, such as the differences between the young and the elderly population and the differences between the economically underdeveloped and developed regions. Second, the air quality control is imminent, and its impact on the natural environment of a country or a region has gradually emerged. So it is necessary to strengthen the environmental governance. In theory, we should not only consider the trend of macroenvironment change, but also pay attention to the loss of microindividuals in the environment change. Third, when we investigate the residents' LS theoretically, we should not only combine the macroeffect of traditional regional economic development, such as regional per capita GDP, but also pay attention to the difference of residents' LS caused by the difference of household per capita income level. Especially when the substitutability between the deterioration of air quality and the improvement of economic income is reduced, priority should be given to the reduction of residents' LS caused by environmental deterioration. And the negative health impact brought by the change of air quality should be paid attention to, so as to implement relevant intervention policies and improve residents' LS.

Abbreviations CHARLS, China Health and Retirement Longitudinal Study; API, air pollution index; AQI, air quality index; LS, life satisfaction; LSA, life satisfaction approach

Availability of data and materials The data that support the findings of this study are openly available at the following URL/DOI: http://charls.pku.edu.cn/.

Code availability Not applicable.

Author contribution H.L. revised it critically for important intellectual content and approved the version to be published and carry out language retouching and modification. T.T.H. made a substantial contribution to the concept and design of the work and interpretation of data and drafted the article.

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Declarations

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