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Evolutionary game analysis of indoor radon mitigation with local government involvement

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ABSTRACT

Radon is the second leading risk factor for lung cancer after smoking. As a public policy, radon mitigation not only involves radon control technology or its cost-benefit analysis, but also includes the decision-making process of local governments. In this study, the evolutionary game theory was used to analyse the interaction between local governments and residents based on the subsidy of the central government. Considering the practical data in China, factors influencing the behaviour of local governments and residents were discussed using numerical simulations. The results indicated that radon mitigation is a fully government-promoted action; thus, its implementation largely depends on the subsidy of the central government and the share of radon control costs borne by the local government. The financial burden for both local governments and residents is a more important determinant than long-term health effects. The relatively poor local economic situation could limit the implementation of radon control. There would be a public policy paradox wherein cities or regions with higher radon risk would have lower willingness for radon control, mainly due to the significantly higher costs of radon control. This work provides reference data for decision-making to implement radon control and is expected to offer some suggestions for local governments.

1. Introduction

Radon (^{222}Rn) is a naturally occurring radioactive gas generated by the decay of uranium in rocks, soil, and groundwater [1]. As radon is released from the ground and building materials, it can accumulate in the indoor air and significantly affect health. Radon and its daughters are widely known to contribute the most to the public dose of natural radiation [1]. According to the World Health Organisation (WHO), radon is the second leading risk factor of lung cancer after smoking [2]. Early epidemiological studies on miners have demonstrated a positive correlation between high-level radon exposure and lung cancer [2]. Additionally, research in recent decades has indicated that radon exposure in buildings increases the risk of lung cancer among residents [3–6]. Furthermore, some studies have found radon to be a risk factor for diseases such as leukaemia [7] and disseminated sclerosis [8].

A study in 2018 indicated that the median attributable fraction of lung cancer deaths due to radon among 66 countries globally ranged from 13.6% to 16.5%. These countries had a total of over 200,000 deaths from lung cancer in 2012 caused by radon exposure [4]. The three largest combined analyses in previous epidemiological research included 13 studies in Europe [9,10], 7 studies in North

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America [11,12], and 2 studies in China [13,14]. These studies provided direct evidence for indoor radon-induced lung cancer and estimated the risk of lung cancer associated with indoor radon exposure. For every 100 $Bq \cdot m^{-3}$ increase in radon concentration, the increased risks of lung cancer were 8% (95% CI: 3%, 16%), 11% (95% CI: 0%, 28%), and 1.3% (95% CI: 1%, 3.6%) respectively. Several methods of radon mitigation have been developed and widely implemented in different countries [15–21]. Previous studies have shown that appropriate treatments conducted in high radon areas can effectively decrease indoor radon concentration and critically reduce its health effects. Furthermore, a Swedish study revealed that reducing the indoor radon concentration from 200 $Bq \cdot m^{-3}$ to 100 $Bq \cdot m^{-3}$ can have additional financial benefits [22]. Petersen indicated that the most economical way to control radon is the treatment of smokers' dwellings, public education, and communication about radon's health risks [23]. Although different international organisations and countries have provided relevant recommendations and standards for radon control, government-level action plans, and financial support remain insufficient in most countries.

One of the important reasons for this is the specificity of radon compared to other pollutants. As a naturally occurring radioactive gas, the perception of radon is not strong enough, which leads to cognitive biases among local governments and the public, such as lack of knowledge and ignorance [24–28]. Compared to some atmospheric pollutants, there are critical city-to-city deviations in the concentration of indoor radon. Even in the same city, different rooms differ in radon levels and their corresponding treatment strategies. Thus, radon mitigation is highly dependent on the participation of local governments and families. Furthermore, the health effects of radon are stochastic and long-term; however, the financial cost of radon mitigation is usually deterministic and short-term. There is a natural dislocation of costs and benefits for radon mitigation. The local government and resident families should be considered as interacting decision-makers to reach a visionary decision.

Current research on radon mitigation has mainly focused on its effectiveness and cost-benefit analysis. However, most of these studies could not meet the specificity of radon or discuss the dislocation of costs and benefits. The evolutionary game analysis is based on the assumption that players learn and adjust their strategies with bounded rationality and incomplete information. It has been utilised in decision-making research on various environmental issues [29–32]. Its evolving patterns of analysis could have potential advantages for radon mitigation. However, few radon-related applications based on evolutionary game analysis have been reported.

In this study, an evolutionary game analysis for radon mitigation was conducted with the involvement of two decision-makers: local governments and resident families. This analysis considered all major factors essential for the decision, including the cost of indoor radon survey and corresponding treatment, typical radon concentration for different cities, radon-induced lung cancer incidence, clinical costs for lung cancer, and indirect economic impact. Based on the data provided by the present and previous studies, the influence of different factors on decision-making was discussed. This study's results are expected to prove beneficial to the government in developing radon action plans in the future.

2. Materials and methods

2.1. Evolutionary game theory

Different from classical game theory, the following aspects show the characteristics of evolutionary game theory: first, the evolutionary game theory holds that participants are bounded and finite, not completely rational, because people's perception, cognition, and expression are limited [33–35]. Second, population is the subject of evolutionary game theory. Individuals can gradually adjust their strategies in multiple games through observation, learning, and imitation, and eventually reach the stable state of all players, namely evolutionary stable strategy (ESS) [36,37]. The complete analytical framework of evolutionary game theory includes the following three parts: the payoff matrix, replication dynamic equation, and evolutionary stability strategy [34,35].

(1) The payoff matrix: The basis of evolutionary game analysis is the payoff matrix. The establishment of the payoff matrix enables us to determine the respective payoffs of all players under different strategy combinations and express them in the form of a matrix.
(2) The replicated dynamic system: The replicated dynamic system is composed of a replicated dynamic equation. In evolutionary game analysis, the evolutionary stable strategy is the static stable state, and the replicated dynamic equation is the dynamic change trajectory that contains the dynamic principle. The replicated dynamic equation describes the relationship between the strategy selected by each player and fitness. As a fundamental concept in the theory of biological evolution, fitness can be explained as an increase in the number of individuals who choose similar strategies after a game [38].
(3) The evolutionary stability strategy: In the process of multiple games, different players gradually modify their strategies through observation, learning, and imitation. As the game continues, most individuals in the group gradually tend towards the stable strategy, and eventually, make different players reach the stable state. When all players have reached a steady state, the combination of strategies each player chooses is called evolutionarily stable [39].

Local governments and residents have different drivers of interest in indoor radon control. When faced with risks, individuals in both groups will compare possible losses and gains to arrive at a decision. As the two groups have different interest demands, they are players in a game on indoor radon control. Due to the limitation of rationality, they are often unable to find the best strategy in a game. Alternatively, they observe and learn from others' behaviour and then decide whether to change strategies. Only after playing several games can they gradually determine the best strategy. The process of determining the optimal strategy conforms to the analytical framework of evolutionary game theory; therefore, this theory can be used to study the construction of an indoor radon control policy.

2.2. Model

2.2.1. Hypothesis

The following hypotheses were proposed before constructing the evolutionary game model between local governments and residents.

(1) In this model, local governments and residents are players with limited rationality, which means that they cannot determine their best strategy in one game, except through multiple games.
(2) In this model, local governments have two strategies: one is to accept subsidies from the central government to implement indoor radon control and reduce the incidence of lung cancer among residents, whereas the second is to choose not to implement indoor radon control and maintain the existing state as the central government does not provide subsidies.
(3) In this model, residents also have two strategies: one is to actively cooperate with indoor radon control and spend a certain amount of money in response to the policy to obtain benefits from the reduced incidence of lung cancer. Second, residents do not cooperate with indoor radon control, do not pay the cost, and at the same time, cannot obtain benefits from the reduced incidence of lung cancer.
(4) When local governments choose to implement indoor radon control, they can obtain subsidies from the central government, reduce medical expenses, and benefit from the social and economic effects caused by the decrease in lung cancer patients. When local governments choose not to implement indoor radon control, the existing medical expenses will be maintained and central government subsidies will be lost.

2.2.2. A two-party game model based on the evolutionary game theory

2.2.2.1. Variables. There are several variables in a two-party game between the local government and residents. All variables are non-negative and are defined as follows:

D: The cost of indoor radon surveys;
k: Share of the cost of indoor radon survey borne by local governments (0–100%);
E: Total cost of indoor radon control;
l: Share borne by local governments in the total cost of indoor radon control (0–100%);
C: Central government subsidies (in this study, the unit is 100,000 CNY);
r_0: Initial radon concentration for indoor radon control;
r: Radon concentration after indoor radon control;
s: Incidence of lung cancer per unit radon concentration (per 100,000 population);
H: The direct cost of lung cancer treatment;
t: The proportion of direct medical expenses for lung cancer borne by local governments (0–100%);
H': Indirect cost of lung cancer treatment;
L: Number of years of incapacity due to illness;
L_1: Per capita disposable income (PCDI);
L_2: Urban per capita GDP;
Y: Local governments' propaganda and education expenses for indoor radon control.

2.2.2.2. Payoff for different players. In the study of indoor radon control, there are four possible strategy combinations as residents and local governments each have two alternative options.

(1) The first situation is when residents choose to cooperate with indoor radon control activities, and local governments choose to implement indoor radon control measures.

The payoff of residents can be calculated as shown in Equation (1):

$$-(1-k)D-(1-l)E-rs[(1-t)H+H'+L_1] \tag{1}$$

where $(1-k)D$ is the cost borne by residents for the indoor radon survey. $(1-l)E$ is the cost borne by residents for indoor radon treatment. $rs[(1-t)H+H'+L_1]$ is the average expected economic loss of residents after lung cancer; $(1-t)H$ is the cost borne by residents in the direct medical economic burden of lung cancer treatment, including outpatient, hospitalisation, and drug expenses. H' is the direct non-medical economic burden borne by residents during lung cancer treatment (including disease-related nutrition expenses, transportation expenses, accommodation expenses, meal expenses, accompanying expenses, and property losses). L_1 is the household income loss caused by the labour loss of residents.

The payoff of local governments can be calculated as shown in Equation (2):

$$C-kD-lE-rs(tH+L_2)-Y \tag{2}$$

where C is the allocation given by the central government to local governments for indoor radon control. kD is the cost borne by local governments for the indoor radon survey. lE is the cost borne by local governments for indoor radon control. $rs(tH+L_1)$ is the average expected economic loss of local governments after residents suffer from lung cancer. tH is the cost borne by local governments in the direct medical economic burden of lung cancer treatment (including outpatient, hospitalisation, and drug expenses). L_2 is the tax revenue lost by local governments because residents are unable to work after developing lung cancer. Y is the cost of publicity and educational activities conducted by local governments for indoor radon control.

(2) The second situation is when residents choose not to cooperate with indoor radon control activities, and local governments choose to implement indoor radon control measures.

The payoff of residents can be calculated as shown in Equation (3):

$$-r_0s[(1-t)H+H^{'}+L_1] \tag{3}$$

where $r_0s[(1-t)H+H^{'}+L_1]$ is the average expected economic loss of residents suffering from lung cancer.

The payoff of local governments can be calculated as shown in Equation (4):

$$C-D-E-r_0s(tH+L_2)-Y \tag{4}$$

where $r_0s[tH+L_2]$ is the average expected economic loss of local governments after residents develop lung cancer.

(3) The third situation is when residents choose to cooperate with indoor radon control activities, but local governments choose not to implement indoor radon control measures.

The payoff of residents can be calculated as shown in Equation (5):

$$-D-E-rs[(1-t)H+H^{'}+L_1] \tag{5}$$

where $rs[(1-t)H+H^{'}+L_1]$ is the average expected economic loss of residents suffering from lung cancer.

The payoff of local governments can be calculated as shown in Equation (6):

$$-rs(tH+L_2) \tag{6}$$

where $rs(tH+L_2)$ is the average expected economic loss of local governments after residents develop lung cancer.

(4) The fourth situation is when residents choose not to cooperate with indoor radon control activities, and local governments choose not to implement indoor radon control measures.

The payoff of residents can be calculated as shown in Equation (7):

$$-r_0s[(1-t)H+H^{'}+L_1] \tag{7}$$

where $-r_0s[(1-t)H+H^{'}+L_1]$ is the average expected economic loss of residents suffering from lung cancer.

The payoff of local governments can be calculated as shown in Equation (8):

$$-r_0s(tH+L_2) \tag{8}$$

where $-r_0s(tH+L_2)$ is the average expected economic loss of local governments after residents develop lung cancer.

Table 1 displays the payoff matrix of both sides of the game.

2.2.2.3. Replicated dynamic equation. The probability that residents will choose to cooperate with indoor radon control activities is assumed to be x, whereas the probability that they will not cooperate with indoor radon control activities is 1- x. Similarly, the probability that local governments will choose to implement indoor radon control and receive subsidies from the central government is y, whereas the probability that local governments will choose not to implement indoor radon control and receive subsidies from the central government is 1- y. U_{ab} refers to the expected payoffs of different players choosing different strategies. $\overline{U_a}$ refers to the average expected payoffs of different players; $a=1$ refers to residents, and $a=2$ refers to local governments. b represents the strategies of different players, where $b=1$ refers to the first strategy and $b=2$ refers to the second strategy. Table 2 describes each symbol.

Table 1
Payoff matrix for both sides of the game.

		Local governments			
		Implementing indoor radon control		Not implementing indoor radon control	
Residents	Cooperating	Residents	$-(1-k)D-(1-l)E-rs[(1-t)H+H^{'}+L_1]$	Residents	$-D-E-rs[(1-t)H+H^{'}+L_1]$
		Local governments	$C-kD-lE-rs(tH+L_2)-Y$	Local governments	$-rs(tH+L_2)$
	Not cooperating	Residents	$-r_0s[(1-t)H+H^{'}+L_1]$	Residents	$-r_0s[(1-t)H+H^{'}+L_1]$
		Local governments	$C-D-E-r_0s(tH+L_2)-Y$	Local governments	$-r_0s(tH+L_2)$

According to the methodology of evolutionary game theory, the expected and average returns of different players under different strategies can be calculated:

The payoffs for residents are:

$$\begin{aligned} U_{11} &= y\{-(1-k)D-(1-l)E-rs[(1-t)H+H^{'}+L_1]\} \\ &+(1-y)\{-D-E-rs[(1-t)H+H^{'}+L_1]\} \\ &= y(kD+lE)-D-E-rs[(1-t)H+H^{'}+L_1] \end{aligned} \tag{9}$$

$$\begin{aligned} U_{12} &= y\{-r_0s[(1-t)H+H^{'}+L_1]\}+(1-y)\{-r_0s[(1-t)H+H^{'}+L_1]\} \\ &= -r_0s[(1-t)H+H^{'}+L_1] \end{aligned} \tag{10}$$

$$\begin{aligned} \overline{U}_1 &= xU_{11}+(1-x)U_{12} \\ &= xy(kD+lE)+x\{(r_0-r)s[(1-t)H+H^{'}+L_1]-D-E\} \\ &-r_0s[(1-t)H+H^{'}+L_1] \end{aligned} \tag{11}$$

where U_{11}, as shown in Equation (9), and U_{12}, as shown in Equation (10), represent the expected benefits of residents choosing or refusing to cooperate with radon control measures, respectively. $\overline{U_1}$, as shown in Equation (11), represents the average payoff of the residents. According to the methodology of evolutionary game theory [34,40], using U_{11}, U_{12} and $\overline{U_1}$, the replication dynamic equation of residents can be calculated, and the result is shown in Equation (12).

$$\begin{aligned} F_1(x) &= \frac{dx}{dt} = x(U_{11}-\overline{U}_1) \\ &= x(1-x)\{y(kD+lE)-D-E+(r_0-r)s[(1-t)H+H^{'}+L_1]\} \end{aligned} \tag{12}$$

The payoffs for local governments are:

$$\begin{aligned} U_{21} &= x[C-kD-lE-rs(tH+L_2)-Y] \\ &+(1-x)[C-D-E-r_0s(tH+L_2)-Y] \\ &= x[(1-k)D+(1-l)E+(r_0-r)s(tH+L_2)] \\ &+C-D-E-r_0s(tH+L_2)-Y \end{aligned} \tag{13}$$

$$\begin{aligned} U_{22} &= x[-rs(tH+L_2)]+(1-x)[-r_0s(tH+L_2)] \\ &= x(r_0-r)s(tH+L_2)-r_0s(tH+L_2) \end{aligned} \tag{14}$$

$$\begin{aligned} \overline{U}_2 &= yU_{21}+(1-y)U_{22} \\ &= y\left\{\begin{array}{c} x[(1-k)D+(1-l)E+(r_0-r)s(tH+L_2)] \\ +C-D-E-r_0s(tH+L_2)-Y \end{array}\right\} \\ &+(1-y)\{x(r_0-r)s(tH+L_2)-r_0s(tH+L_2)\} \end{aligned} \tag{15}$$

where U_{21}, as shown in Equation (13), and U_{22}, as shown in Equation (14), represent the expected benefits of local governments choosing or refusing to implement indoor radon control and receive subsidies from the central government, respectively. $\overline{U_1}$, as shown in Equation (15), represents the average payoff of local governments. Similarly, using U_{21}, U_{22} and $\overline{U_2}$, the replication dynamic equation of local governments can be calculated, and the result is shown in Equation (16).

$$\begin{aligned} F_2(y) &= \frac{dy}{dt} = y(U_{21}-\overline{U}_2) \\ &= y(1-y)\{x[(1-k)D+(1-l)E]+C-D-E-Y\} \end{aligned} \tag{16}$$

By combining Equations (12) and (16), the replicated dynamic system of the two-party evolutionary game model can be obtained, as shown in Equation (17).

Table 2
Description of each symbol.

Symbol	Description
x	The probability that residents will choose to cooperate with indoor radon control
1 - x	The probability that residents will choose not to cooperate with indoor radon control
y	The probability that local governments will choose to implement indoor radon control
1 - y	The probability that local governments will choose not to implement indoor radon control
U_{11}	The expected payoffs when residents choose to cooperate with indoor radon control
U_{12}	The expected payoffs when residents choose not to cooperate with indoor radon control
U_{21}	The expected payoffs when local governments choose to implement indoor radon control
U_{22}	The expected payoffs when local governments choose not to implement indoor radon control
$\overline{U_1}$	The average payoff of residents
$\overline{U_2}$	The average payoff of local governments

$$\begin{cases} F_1(x) = \frac{dx}{dt} = x(1-x)\left\{ \begin{array}{c} y(kD+lE)-D-E \\ +(r_0-r)s[(1-t)H+H'+L_1] \end{array} \right\} \\ F_2(y) = \frac{dy}{dt} = y(1-y)\{x[(1-k)D+(1-l)E]+C-D-E-Y\} \end{cases} \tag{17}$$

2.2.2.4. Evolutionary stable strategies (ESS). When the replication dynamic equations equal 0, the stable state of the system can be obtained, as shown in Equation (18).

$$\begin{cases} F_1(x) = \frac{dx}{dt} = x(1-x)\left\{ \begin{array}{c} y(kD+lE)-D-E \\ +(r_0-r)s[(1-t)H+H'+L_1] \end{array} \right\} = 0 \\ F_2(y) = \frac{dy}{dt} = y(1-y)\{x[(1-k)D+(1-l)E]+C-D-E-Y\} = 0 \end{cases} \tag{18}$$

The initial values of the two players were set as *x (0)* and *y (0)*. To solve Equation (18), five equilibrium points were obtained: $E_1(0,0)$, $E_2(0,1)$, $E_3(1,0)$, $E_4(1,1)$ and $E_5(x^*, y^*)$. Equation (19) was solved to obtain $E_5(x^*, y^*)$.

$$\begin{cases} y(kD+lE)-D-E+(r_0-r)s[(1-t)H+H'+L_1]=0 \\ x[(1-k)D+(1-l)E]+C-D-E-Y=0 \end{cases} \tag{19}$$

The results of Equation (19) can be calculated as shown in Equation (20):

$$\begin{cases} x^* = \frac{D+E+Y-C}{(1-k)D+(1-l)E} \\ y^* = \frac{D+E-(r_0-r)s[(1-t)H+H'+L_1]}{kD+lE} \end{cases} \tag{20}$$

After obtaining these five equilibrium points, new conditions need to be introduced to determine whether these five equilibrium points are the final stable points of the system. Based on the basic attributes of the evolutionary stability strategy proposed by Friedman, the evolutionary stability strategy must satisfy the pure strategy Nash equilibrium when the Nash equilibriums of other forms are not likely to be the stability strategy in the system [41]. Therefore, $E_5(x^*, y^*)$, as a mixed-strategy Nash equilibrium, cannot be the final stable point of the system. The stability of the other four points can be determined by introducing Lyapunov's System Stability Theory [42]. Based on this theory, the stability of the system can be determined using the eigenvalues of the corresponding matrix; that is, if all eigenvalues of the matrix are negative, the system is stable. Alternatively, if all eigenvalues of the matrix are non-positive and the eigenvalues of 0 do not have multiple roots, the system is determined to be stable in Lyapunov's theory; otherwise, the system is unstable [43,44].

To determine whether the equilibrium point is an ESS, the coordinates of points ($E_1 \sim E_4$) were entered into the system to obtain the corresponding Jacobian matrix, which is represented by $J_1 \sim J_4$, respectively, as shown in Equations (21)–(24).

$$J_1 = \begin{vmatrix} (r_0-r)s[(1-t)H+H'+L_1]-D-E & 0 \\ 0 & C-D-E-Y \end{vmatrix} \tag{21}$$

$$J_2 = \begin{vmatrix} (r_0-r)s[(1-t)H+H'+L_1]-(1-l)D-(1-l)E & 0 \\ 0 & D+E+Y-C \end{vmatrix} \tag{22}$$

$$J_3 = \begin{vmatrix} D+E-(r_0-r)s[(1-t)H+H'+L_1] & 0 \\ 0 & C-kD-lE-Y \end{vmatrix} \tag{23}$$

Table 3
Stability of E_1–E_4 under different conditions.

	$C > C_1$	$C = C_1$	$C_2 < C < C_1$	$C = C_2$	$C < C_2$
$A > A_1$	E_4	E_4	E_4	-	E_3
$A = A_1$	E_4	E_4	E_4	-	-
$A_2 < A < A_1$	E_4	E_4	E_1, E_4	E_1	E_1
$A = A_2$	-	-	E_1	E_1	E_1
$A < A_2$	E_2	-	E_1	E_1	E_1

Notes: $C_1 = D + E + Y$; $C_2 = kD + lE + Y$; $A = (r_0 - r)s[(1-t)H + H' + L_1]$; $A_1 = D + E$; $A_2 = (1-k)D + (1-l)E$.

$$J_4 = \begin{vmatrix} (1-k)D + (1-l)E - (r_0 - r)s[(1-t)H + H^{'} + L_1] & 0 \\ 0 & kD + lE + Y - C \end{vmatrix} \quad (24)$$

The stability of E_1–E_4 under different conditions can be obtained using the Jacobian matrix. The stability points are shown in Table 3.

As shown in Tables 3 and if E_4 is expected to be the final stable point, the following inequality group (25) should be true:

$$\begin{cases} (r_0 - r)s[(1-t)H + H^{'} + L_1] > (1-k)D + (1-l)E \\ C > kD + lE + Y \end{cases} \quad (25)$$

Inequality group (25) provides guidance for parameter adjustment in the subsequent simulation.

2.3. Values of parameters

In this study, 100,000 people were considered as the standard unit of population, with the assumption that each household has two residents on average.

Based on the database of residential radon concentration in Chinese cities established in our previous study, the population-weighted average indoor radon concentration of Chinese residents in the 2010s was approximately 52.3 $Bq{\cdot}m^{-3}$ [45]. The average concentration for different cities ranged from less than 20 $Bq{\cdot}m^{-3}$ to approximately 80 $Bq{\cdot}m^{-3}$. In the present study, the initial baseline of the indoor radon concentration was set as 52.3 $Bq{\cdot}m^{-3}$.

The Chinese national standard (GB/T 16146-2015) suggests 100 $Bq{\cdot}m^{-3}$ as the target level for new buildings. Rooms with radon over 100 $Bq{\cdot}m^{-3}$ were treated in this study. Many previous surveys have confirmed that indoor radon concentrations follow a log-normal distribution. According to a national survey conducted in 26 cities [46], the average radon concentration was 43.8 $Bq{\cdot}m^{-3}$, whereas the percentage of rooms with radon over 100 $Bq{\cdot}m^{-3}$ and 200 $Bq{\cdot}m^{-3}$ was approximately 6.4% and 0.7%, respectively. Based on these results, the standard deviation of the log of this distribution σ was estimated to be approximately 0.5. Thus, for a given average radon concentration in a city, the percentage of rooms with radon over 100 $Bq{\cdot}m^{-3}$ and 200 $Bq{\cdot}m^{-3}$ could be easily estimated in this study.

Large-scale surveys are the foundation for targeting rooms with relatively high radon levels. The price of the survey is approximately 100 Chinese CNY per household, which could possibly drop due to the government's large order. Empirically, the survey that combines random sampling and focused screening should cover at least 10% of the total rooms to determine those with relatively high radon levels. Therefore, the cost of an indoor radon survey is 500,000 CNY per 100,000 population ($D = 500{,}000$), which is borne by the government in practice ($k = 100\%$). The local government could increase the cost over 10 years.

For rooms with a radon concentration between 100 $Bq{\cdot}m^{-3}$ and 200 $Bq{\cdot}m^{-3}$, the main method for radon mitigation is mechanical ventilation. As a reasonable assumption in the calculation, mechanical ventilation would decrease the concentration by approximately 50 $Bq{\cdot}m^{-3}$ and cost 100 CNY per year. For rooms with a radon concentration greater than 200 $Bq{\cdot}m^{-3}$, more complex methods should be used, such as shielding the radon sources and air purification, which would decrease the concentration by approximately 150 $Bq{\cdot}m^{-3}$ and cost 1000 CNY per year.

The crude incidence of lung cancer in the Chinese standard population is 57.26/100,000 [47]. The WHO states that every 100 $Bq{\cdot}m^{-3}$ increase in radon concentration would lead to a 16% increase in the risk of lung cancer [2]. Therefore, the average incidence of lung cancer caused by indoor radon concentration per $Bq{\cdot}m^{-3}$ was calculated to be 0.092 per 100,000 population.

A previous survey indicated that the direct cost of lung cancer treatment in China is approximately 80,786 CNY [48]. We assumed that 60% of the costs are borne by local governments through medical insurance. Since few studies have examined the indirect cost of lung cancer treatment, and the amount varies greatly due to different accounting methods, this study assumed that the indirect cost of lung cancer treatment is 20,000 CNY per case.

Additionally, the income lost due to the inability of the residents to work due to lung cancer was considered in the calculation, which was set to be the per capita disposable income for five years. The local government would also lose the corresponding GDP and local tax for five years. In this study, the per capita disposable income and per capita GDP of China were obtained from the statistical data of the National Bureau of Statistics, PRC in 2020.

The subsidy from the central government was set at 15 CNY per person. Simultaneously, we assumed that the education cost of the local government for indoor radon control would be 10,000 CNY per 100,000 population.

Part of the parameter settings in this study are shown in Table 4.

Table 4
Part of the parameter settings.

D	k	s	t	H	H'	L	Y
500,000	100%	0.092	60%	80786	20000	5	10000

Notes: *D*: The cost of indoor radon surveys; *k*: Share of the cost of indoor radon surveys borne by local governments; *s*: Incidence of lung cancer per unit radon concentration (per 100,000 population); *H*: The direct cost of lung cancer treatment; *t*: The proportion of direct medical expenses for lung cancer borne by local governments; *H'*: The indirect cost of lung cancer treatment; *L*: Number of years of incapacity due to the illness; *Y*: Local governments' propaganda and education expenses for indoor radon control.

3. Simulation results

3.1. Situation using initial parameters

Table 5 shows the initial parameters. Under these parameters, the system finally stabilised when radon control measures were implemented by local governments with residents' cooperation. The results are shown in Fig. 1, which can be considered as the baseline in this study.

Fig. 1a and b demonstrates that the simulation under different parameters consists of 81 groups of different initial probabilities (i.e. $(x = 0.1, y = 0.1)$, $(x = 0.1, y = 0.2)$, …, $(x = 0.1, y = 0.9)$, $(x = 0.2, y = 0.1)$, $(x = 0.2, y = 0.2)$, …, $(x = 0.9, y = 0.9)$). Under various parameter settings in the simulation, the model was stable in the state where local governments were willing to implement indoor radon control measures and residents were willing to cooperate. The results indicated that it would be feasible to implement radon control measures under the national average radon level and economic situation if appropriate subsidies could be provided.

It can be observed that the higher the initial probabilities of the local governments and residents, the faster the stable state could be reached. The initial probability indicates the initial willingness of local governments and residents. Furthermore, in this evolutionary process, the willingness of local governments reached a stable state much faster than that of residents. Thus, the convergence steps of the entire system depend on the initial willingness of residents. It would be beneficial to promote the smooth implementation of the radon control policy by strengthening the education about radon-related health risks for the public and stimulating residents' enthusiasm.

3.2. Situation of reducing the share of costs borne by local governments

To explore the influence of different shares of indoor radon control costs borne by local governments on the replicable dynamic system, the share of indoor radon control costs borne by local governments was reduced from 85% to 60%. The specific parameter settings are listed in Table 6. As shown in Fig. 2a and b, the system finally stabilised when local governments implemented the radon control measures without the cooperation of residents.

Fig. 2a and b indicates that a relatively low share of indoor radon control costs borne by local governments will lead to residents' reluctance to cooperate with indoor radon control measures. For local governments, reducing the share of costs has no obvious influence on their decision to implement indoor radon control measures. However, residents need to bear more indoor radon control costs. If the residents' expenditure is greater than the corresponding benefits of indoor radon control, the residents would ultimately choose to ignore the measures. Therefore, the results revealed that a large share of indoor radon control costs borne by local governments is necessary to gain the cooperation of residents.

3.3. Situation for different central government subsidies

To explore the influence of different central government subsidy amounts on the replication dynamic system, the central government subsidy amounts were set to 0, 5, 10, 15, and 20 (15 was set as the baseline). The specific parameters are listed in Table 7. As shown in Fig. 3a–d, in the case where the central government's subsidy amount was 0 or 5, the replicative dynamic system quickly stabilised when neither the local government nor residents support the radon control measures. When the subsidy amount of the central government increased (in Fig. 3f–h), the replicative dynamic system stabilised when the local government implemented radon control measures with residents' cooperation. With an increase in the subsidy amount, the convergence steps for the system to stabilise were shortened.

The simulations demonstrated that subsidies from the central government could significantly influence the final result of the evolutionary process. Local governments had no endogenous motivation to implement radon control measures at the current economic level; thus, subsidies could be considered as their original motivation. When the subsidy amount of the central government increases to a certain level, the strategic choices of local governments would gradually change and finally gain the cooperation of residents. Therefore, setting a reasonable amount of central government subsidies is an extremely critical step. Based on inequality group (25), the critical subsidy point for local governments to implement indoor radon control measures and obtain residents' cooperation under specific circumstances can be calculated. In this case, the critical subsidy point is 6.9 CNY per person. Under practical situations, the central government would need to pay slightly more than the critical point to have acceptable convergence steps to reach a consensus with local governments and residents.

Table 5
Settings of initial variable values.

l	C	r_0	L_1	L_2
85%	15	52.3	32189	71828

Notes: l: Share borne by local governments in the total cost of indoor radon control (0–100%); C: Central government subsidies (in this study, the unit is 100,000 CNY); r_0: Initial radon concentration for indoor radon control; L_1: Per capita disposable income (PCDI); L_2: Urban per capita GDP.

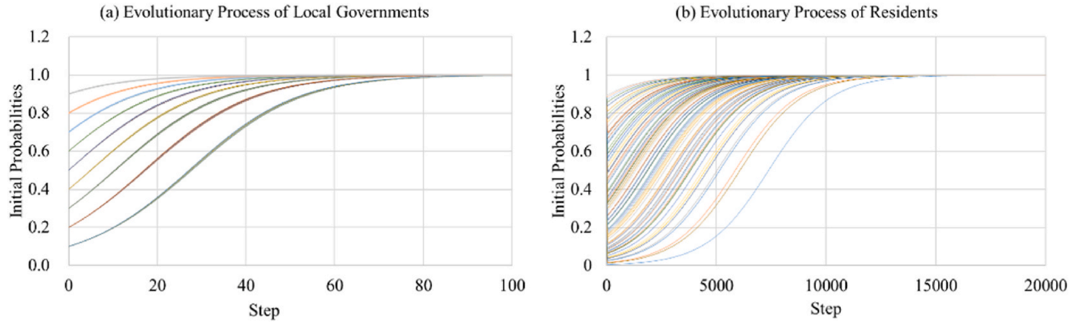

Fig. 1. Evolutionary process for the initial situation (Under the parameters set in Table 5, Fig. 1a illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 1b illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control.).

Table 6
Settings of variable values in the simulation for reducing the share of costs borne by local governments.

l	C	r_0	L_1	L_2
60%	15	52.3	32189	71828

Notes: *l*: Share borne by local governments in the total cost of indoor radon control (0–100%); *C*: Central government subsidies (in this study, the unit is 100,000 CNY); r_0: Initial radon concentration for indoor radon control; L_1: Per capita disposable income (PCDI); L_2: Urban per capita GDP.

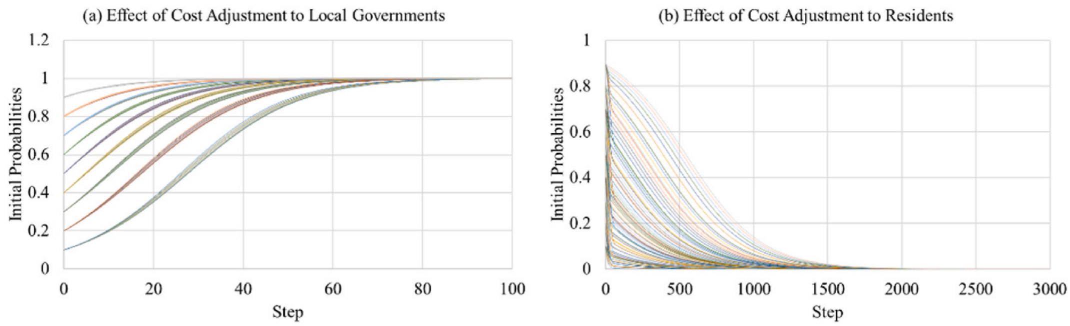

Fig. 2. Evolutionary process for reduced share of costs borne by local governments (With reducing share borne by local governments in the total cost of indoor radon control to 60%, Fig. 2a illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 2b illustrates the evolutionary process of residents, indicating their choice of not cooperating with indoor radon control.).

Table 7
Settings of variable values in the simulation for different subsidies.

l	C	r_0	L_1	L_2
85%	0/5/10/20	52.3	32189	71828

Notes: *l*: Share borne by local governments in the total cost of indoor radon control (0–100%); *C*: Central government subsidies (in this study, the unit is 100,000 CNY); r_0: Initial radon concentration for indoor radon control; L_1: Per capita disposable income (PCDI); L_2: Urban per capita GDP.

3.4. Situation for different per capita disposable income (PCDI) levels

Two provincial-level administrative regions in China, Gansu, and Shanghai, were selected to represent regions with the lowest and highest PCDI levels, respectively. Tables 8 and 9 show the specific parameter settings with PCDI summarised in 2020. As shown in Fig. 4a–d, in Gansu Province with low PCDI, the replication dynamic system stabilised when the local government implemented radon control measures without residents' cooperation. However, in Shanghai, the replicative dynamic system stabilised when the local government implemented radon control measures with residents' cooperation. The convergence steps to reach a stable state in Shanghai were shorter than those in the baseline. Therefore, the higher the PCDI, the higher the enthusiasm of residents. Since the PCDI determines the cost for local residents suffering from lung cancer, it could be considered a key factor influencing their

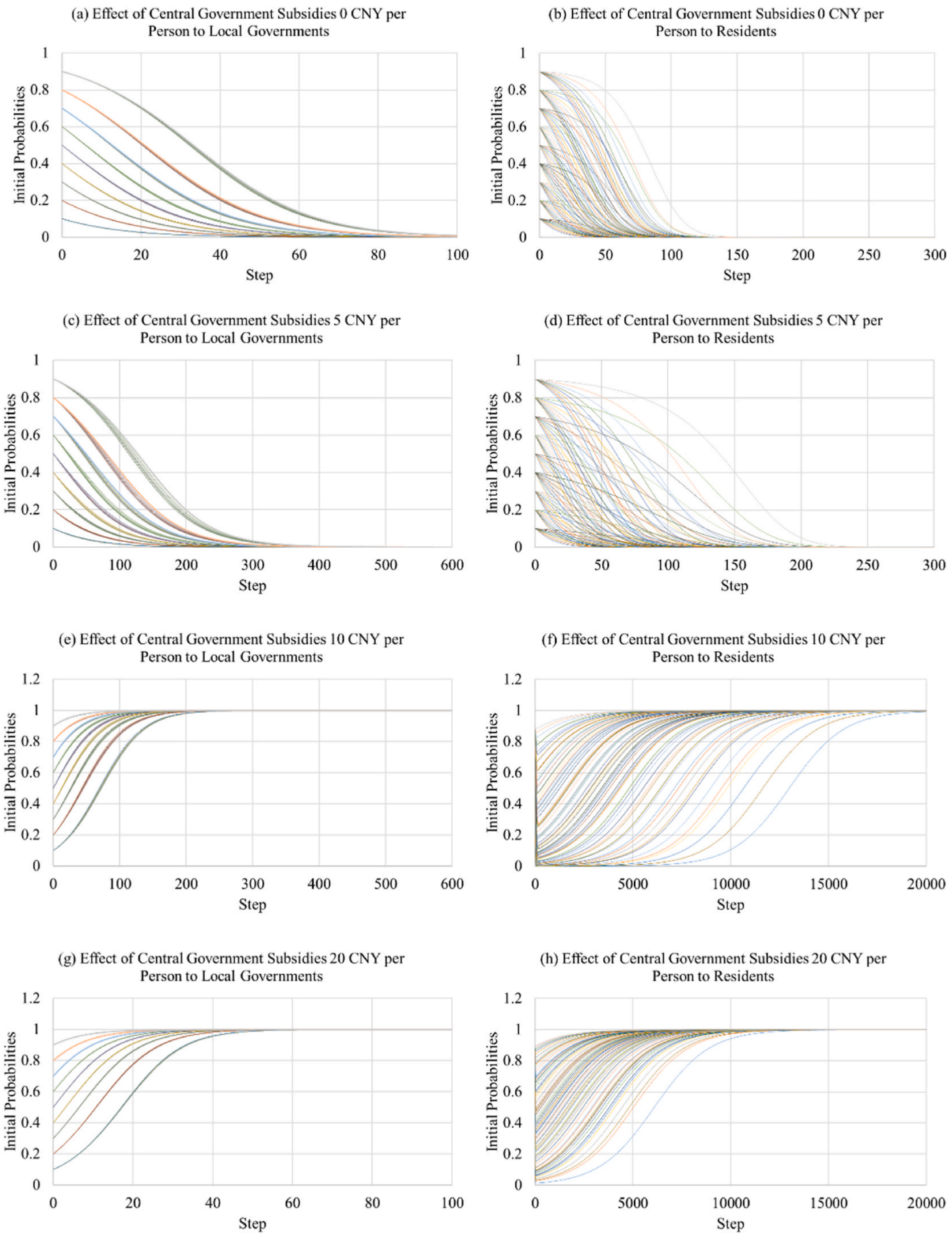

Fig. 3. Evolutionary process for different subsidies (With setting the central government subsidy amounts to 0, Fig. 3a illustrates the evolutionary process of local governments, indicating their choice of not implementing indoor radon control; Fig. 3b illustrates the evolutionary process of residents, indicating their choice of not cooperating with indoor radon control. With setting the central government subsidy amounts to 5, Fig. 3c illustrates the evolutionary process of local governments, indicating their choice of not implementing indoor radon control; Fig. 3d illustrates the evolutionary process of residents, indicating their choice of not cooperating with indoor radon control. With setting the central government subsidy amounts to 10, Fig. 3e illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 3f illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control. With setting the central government subsidy amounts to 20, Fig. 3g illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 3h illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control.).

Table 8
Settings of variable values in Gansu with low PCDI.

l	C	r_0	L_1	L_2
85%	15	52.3	20335	35995

Notes: *l*: Share borne by local governments in the total cost of indoor radon control (0–100%); *C*: Central government subsidies (in this study, the unit is 100,000 CNY); r_0: Initial radon concentration for indoor radon control; L_1: Per capita disposable income (PCDI); L_2: Urban per capita GDP.

Table 9
Settings of variable values in Shanghai with high PCDI.

l	C	r_0	L_1	L_2
85%	15	52.3	72232	155768

Notes: *l*: Share borne by local governments in the total cost of indoor radon control (0–100%); *C*: Central government subsidies (in this study, the unit is 100,000 CNY); r_0: Initial radon concentration for indoor radon control; L_1: Per capita disposable income (PCDI); L_2: Urban per capita GDP.

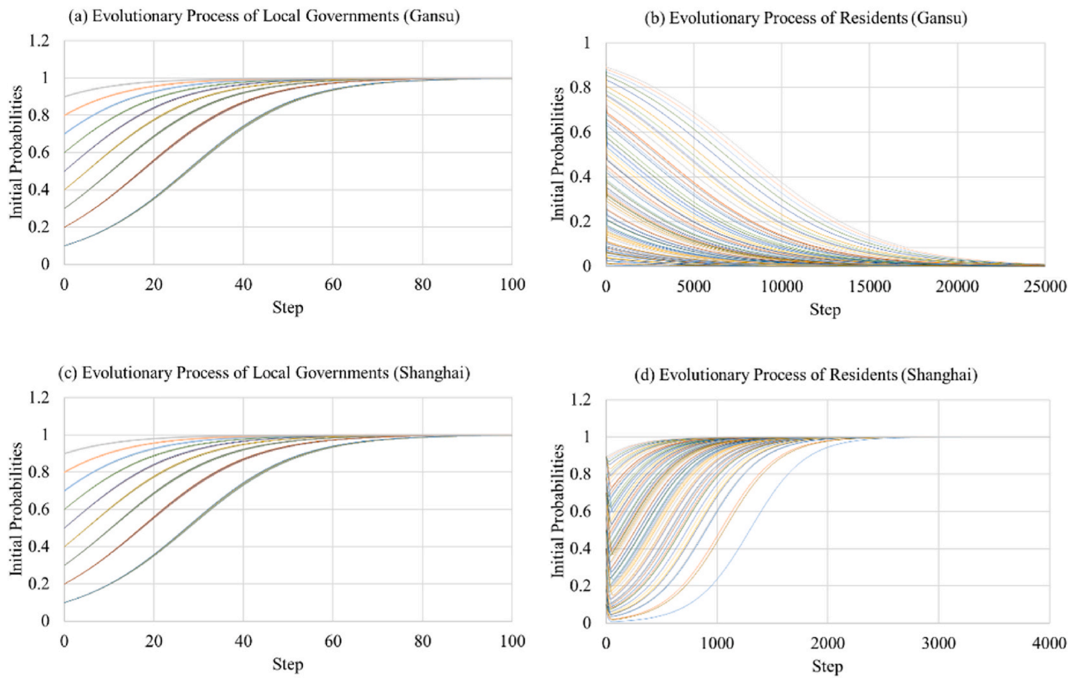

Fig. 4. Evolutionary process for different PCDI levels (With setting PCDI to Gansu level, Fig. 4a illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 4b illustrates the evolutionary process of residents, indicating their choice of not cooperating with indoor radon control. With setting PCDI to Shanghai level, Fig. 4c illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 4d illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control.).

endogenous motivation. For local governments, the PCDI is an indirect index for the local economy. A higher PCDI also indicates that the local government had better financial capability for its public policy, including radon control.

To implement indoor radon control in Gansu, the proportion of indoor radon control costs borne by local governments (*l*) were increased; the specific parameters are listed in Table 10. As shown in Fig. 5a and b, after the proportion of indoor radon control costs borne by local governments (*l*) reached 90%, the replicative dynamic system stabilised when the local government implemented radon

Table 10
Settings of variable values in Gansu with low PCDI and high share of costs borne by local governments.

l	C	r_0	L_1	L_2
90%	15	52.3	72232	155768

control measures with residents' cooperation.

The results revealed that the local economic situation would significantly influence the decision concerning radon-related issues. In our previous study [45], historical data confirmed that the total sample size of radon surveys in the last four decades for different provinces of China had a significant positive correlation with the local GDP. However, a large number of cities located in high radon risk regions in China have relatively low PCDI or GDP. Thus, these cities would require extra support from the central government.

3.5. Situation for reducing the marginal cost of radon investigation and control

The marginal cost of radon investigation and control could decrease by improving technology and increasing the quantity. The cost of radon investigation and control was reduced to 20% or 50% of its original price. The results are shown in Fig. 6a–d.

The results indicated that reducing the marginal cost based on the initial state of this study would have a slight effect on shortening the convergence steps in the evolutionary process. As the saving from the cost is mainly beneficial to the local government, it could be expected that a lower cost would lead to a lower demand for central government subsidies.

3.6. Situation for different initial indoor radon concentrations

To explore the changes in the replication dynamic system under different indoor radon concentrations, the initial indoor radon concentration was assumed to be 40 $Bq{\cdot}m^{-3}$, 60 $Bq{\cdot}m^{-3,}$ and 100 $Bq{\cdot}m^{-3}$, respectively. Table 11 presents the specific parameter settings. As shown in Fig. 7a–h, the replicative dynamic system stabilised when the local government implemented radon control measures with residents' cooperation and the indoor radon concentration was adjusted to 40 $Bq{\cdot}m^{-3}$ and 60 $Bq{\cdot}m^{-3}$, respectively. When the initial radon concentration was higher than 80 $Bq{\cdot}m^{-3}$, the local government and residents would make the exact opposite decision.

The results revealed a public policy paradox that cities or regions with higher radon risk would have lower willingness toward radon control. In this situation, the simulation indicated that the cost of radon control would be significantly higher than the extra cost of radon risk without control measures for both local governments and residents. This paradox was mainly due to the financial burden on local governments and residents.

Table 12 lists the settings of three situations with extra financial support from central governments. The corresponding simulation results are shown in Fig. 8a–f. The result indicated that when the radon concentration was 80 $Bq{\cdot}m^{-3}$, the decision would be reversed if the central government subsidy could reach 30 CNY per person. However, when the radon concentration was 100 $Bq{\cdot}m^{-3}$ and the central government subsidy was increased to 50 CNY/person, it still could not obtain residents' cooperation. Only if the share of indoor radon control costs borne by local governments increased from 85% to 90% would the replication dynamic system stabilise in the state where local governments implement radon control measures with residents' cooperation.

4. Discussion

Based on the evolutionary game theory, we established a model with local governments and residents as two sides of the game and introduced parameters such as the share of indoor radon control costs borne by local governments, the amount of central government subsidies, PCDI, radon investigation and control costs and average indoor radon concentration to establish a reliable simulation model. Most of the parameters used in the model were based on historical data, and the remaining were derived from reasonable assumptions. This study revealed some interesting phenomena, which could enhance our understanding of radon mitigation as well as the interactions between different acting subjects.

The results of the evolutionary game indicated that radon mitigation should be regarded as a fully government-promoted public affair. Cost is a decisive factor in decision-making. Considering the earnings with uncertainty but inevitable spending, residents have little motivation to spontaneously implement radon mitigation without the support of the local government. In each case, the residents

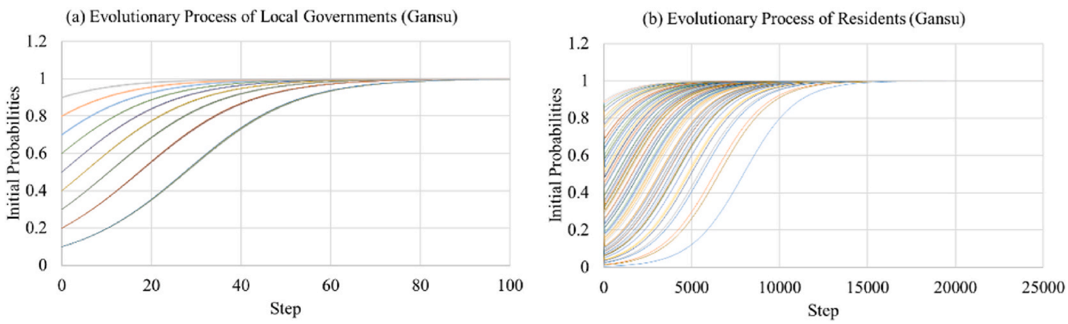

Fig. 5. Evolutionary process for Gansu's PCDI and high share of costs borne by local governments (With setting PCDI to Gansu level and share of costs borne by local governments to 90%, Fig. 5a illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 5b illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control.).

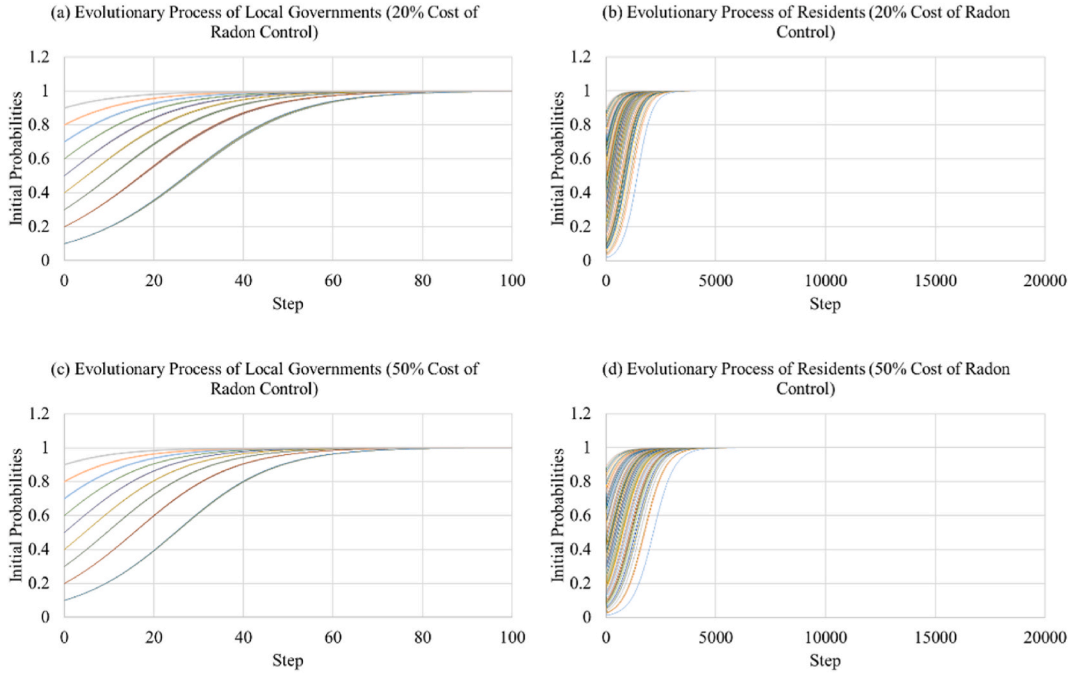

Fig. 6. Evolutionary process of different costs of radon investigation and control (With reducing the marginal cost of radon investigation and control to 20%, Fig. 6a illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 6b illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control. With reducing the marginal cost of radon investigation and control to 50%, Fig. 6c illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 6d illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control.).

Table 11
Settings of variable values in the simulation of different concentrations.

l	C	r_0	L_1	L_2
85%	15	40/60/80/100	32189	71828

Notes: *l*: Share borne by local governments in the total cost of indoor radon control (0–100%); *C*: Central government subsidies (in this study, the unit is 100,000 CNY); r_0: Initial radon concentration for indoor radon control; L_1: Per capita disposable income (PCDI); L_2: Urban per capita GDP.

would be unsupportive once the local government forsakes the implementation of the radon control policy. For local governments, the amount of central government subsidies is a key factor influencing their final decision. As radon is a type of natural radioactive air pollutant, the government does not have enough policy space as that available for other artificial pollutants. Some common policy tools, such as strict standards and penalties, are not fully suitable for radon mitigation. Thus, financial support has become the main driving force behind this issue. If technological advancement reduces costs or the market size reduces marginal costs, it will have little impact on the decision making in the current situation. The only benefit would be a reduction in the burden of central subsidies.

In this evolutionary game, the choices were between 'more losses' and 'fewer losses' for both local governments and residents. Loss aversion is another important motivator of decision-making. The main losses of radon exposure are health risks and time loss of the labour force, which are associated with local economic development. However, there are a few regional differences in the costs of radon control. It finally leads to different decision-making tendencies for local governments and residents in regions with different economic levels. For regions with relatively higher GDP and PCDI, the labour force time lost would be more expensive, which would eventually lead to a higher willingness to support radon control. For economically undeveloped regions, the decision-making tendencies are the opposite. Extra financial support from the central government would be necessary to reverse this result.

The initial average indoor radon concentration could also have influenced the results. The results of this evolutionary game revealed that a higher radon risk would lead to a lower willingness to control radon. From the perspective of public health, this is a contradiction between need and will. If radon control is regarded as a public action that mainly depends on the government's financial support, it would be just a common case of the public policy paradox. Some regions in western China have both, limited economic level and relatively high radon concentration, which would result in a greater challenge in radon control. Therefore, it is necessary for the central government to implement special support policies for these regions to resolve this paradox.

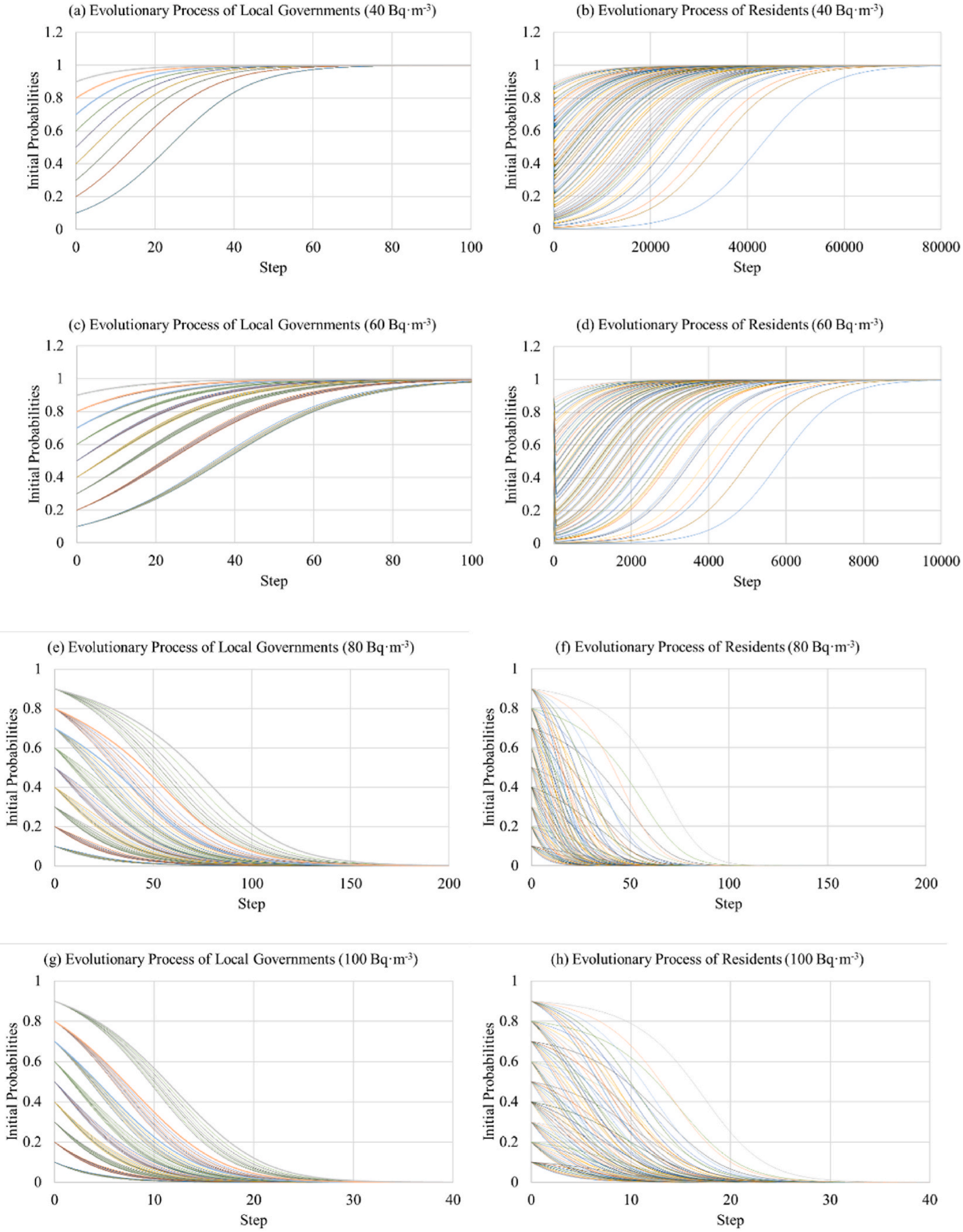

Fig. 7. Evolutionary process for different concentrations (With setting indoor radon concentration to 40 Bq·m^{-3}, Fig. 7a illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 7b illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control. With setting indoor radon concentration to 60 Bq·m^{-3}, Fig. 7c illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 7d illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control. With setting indoor radon concentration to 80 Bq·m^{-3}, Fig. 7e illustrates the evolutionary process of local governments, indicating their choice of not implementing indoor radon control; Fig. 7f illustrates the evolutionary process of residents, indicating their choice of not cooperating with indoor radon control. With setting indoor radon concentration to 100 Bq·m^{-3}, Fig. 7g illustrates the evolutionary process of local governments, indicating their choice of not implementing indoor radon control; Fig. 7h illustrates the evolutionary process of residents, indicating their choice of not cooperating with indoor radon control.).

Table 12
Settings of variable values in three situations with extra financial support from the central government.

l	C	r_0	L_1	L_2
85%	30	80	32189	71828
85%	50	100	32189	71828
90%	50	100	32189	71828

Notes: *l*: Share borne by local governments in the total cost of indoor radon control (0–100%); *C*: Central government subsidies (in this study, the unit is 100,000 CNY); r_0: Initial radon concentration for indoor radon control; L_1: Per capita disposable income (PCDI); L_2: Urban per capita GDP.

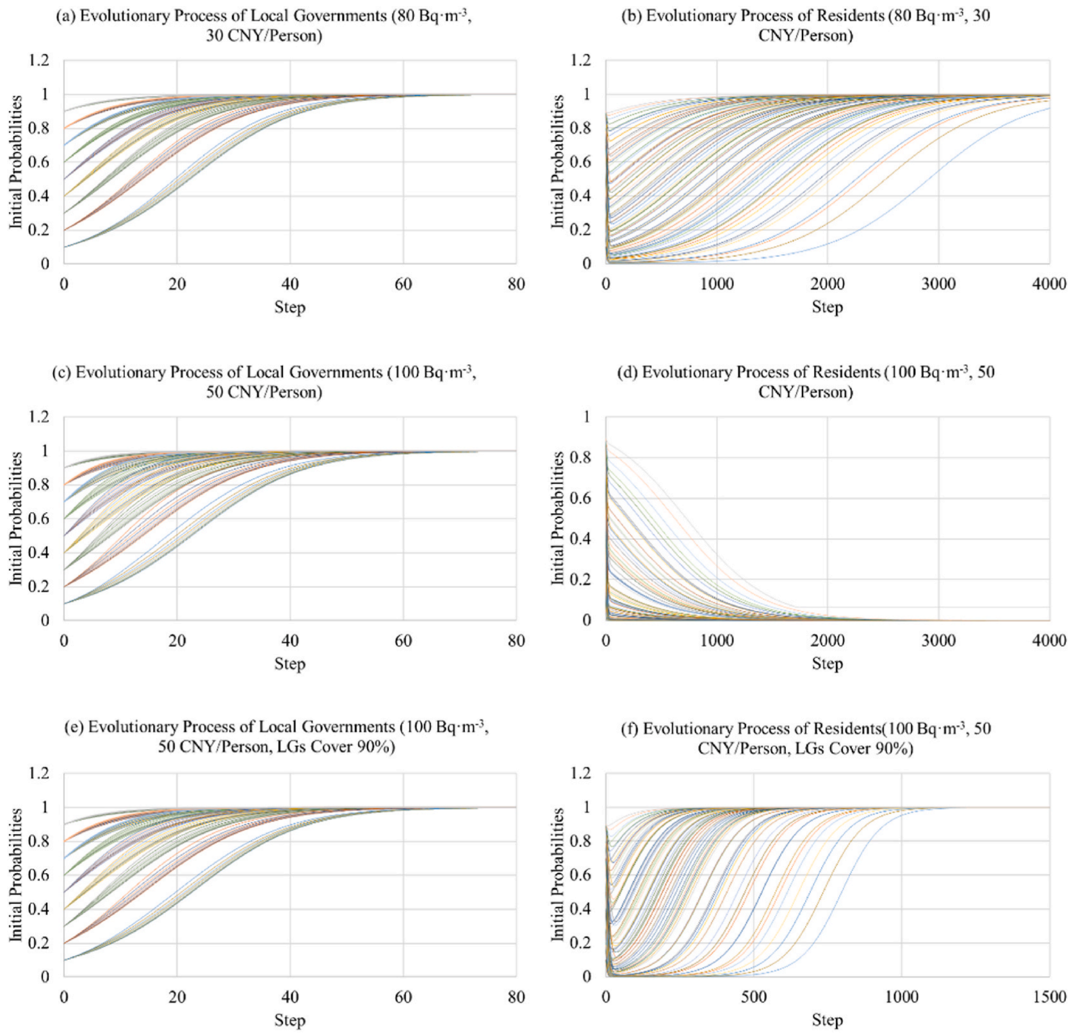

Fig. 8. Evolutionary process of three situations with extra financial support from the central government (Under the parameters set in Table 12, Fig. 8a illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 8b illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control; Fig. 8c illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 8d illustrates the evolutionary process of residents, indicating their choice of not cooperating with indoor radon control; Fig. 8e illustrates the evolutionary process of local governments, indicating their choice of implementing indoor radon control; Fig. 8f illustrates the evolutionary process of residents, indicating their choice of cooperating with indoor radon control.).

5. Conclusions and recommendations

Aiming at the indoor radon control policy, this study constructed an evolutionary game model in which local governments and residents were on two sides of the game and obtained the payoff matrix of both sides and the strategy combination adopted by both sides under different circumstances. By discussing the main influencing factors, this study is expected to provide recommendations for government decision-making.

Financial support from the central government is the primary driving force of radon control for both local governments and residents. Differentiated strategies could be considered to encourage local governments with better economic conditions to take the lead in implementing policies or to provide special support for regions with limited economic levels and relatively high radon concentrations. Other policy tools, such as formulating laws and regulations, could also be considered as an option for areas with extremely high indoor radon concentrations.

For local governments, local conditions (including economic development level, average indoor radon concentration, population, local government financial revenue, etc.) should be comprehensively considered in implementing plans for indoor radon control policies. Furthermore, it would be worth strengthening the publicity and education on indoor radon risk and improving the participation enthusiasm of residents.

Data availability statement

Data included in article/supp. material/referenced in article.

CRediT authorship contribution statement

Dapeng Lin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Weihai Zhuo:** Conceptualization, Methodology, Data curation, Formal analysis, Supervision. **Yupeng Yao:** Conceptualization, Methodology, Data curation, Formal analysis. **Ziqi Qiang:** Data curation, Formal analysis. **Bo Chen:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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