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Impact of regional human capital and urban sprawl on forest ——based on a forest conservation model①

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Abstract

Metropolitan cities in China have become a major economic hubs with an unprecedented increase of land use and decline of environmental resources. Based on a simple and abstract forest conservation model, this paper attempts to explain changes of forest resources caused by urban sprawl. Through the research, it is found that high level of regional human capital is beneficial to curb urban sprawl. In this vein the model presents the urban forest conservation cost strategy at the Nash equilibrium of varied discount factor and parameter control.

Key words: regional human capital, urban sprawl, Nash equilibrium, forest conservation model, cross-sectional econometric model

0 Introduction

With the development of global economy, urban sprawl poses a serious threat to stable economic growth, sustainable environment development and human health. The local ecosystem problems of urban sprawl gradually expand to a larger spatial range and lead to multi-chain and multi-level forest ecological crisis and climate change. The forest around the city has been encroached heavily, greatly reducing the natural carbon storage of the ecosystem[1]. Houghton[2] argued that the worldwide destruction of forests by urban sprawl did not only concentrate on tropical rainforests, but also in many temperate regions. Based on INVEST and cellular automata, Wu et al.[3] verified that high-carbon density forests in Guangdong were the main new sources for urban sprawl, which will reduce carbon storage by 55.07%. Zhu et al.[4] applied the V-I-S urban land cover model and decision tree model to classify and evaluate the loss of forest carbon pool caused by spatial-temporal evolution of land in Urumqi, China. Park[5] explained severe challenges posed by forest degradation around cities to sustainable economic development in Africa.

The concept of urban sprawl has never been clear and unified, and its connotation is constantly adjusted with the change of time. Gottman[6] believed that urban sprawl was the continuous expansion of the edge of the metropolis. Ottensmann[7] proposed that urban sprawl was the discontinuous distribution of land development. Paul[8] compared urban sprawl with pornography, and the fuzziness made it impossible to give the concept accurately and could only be identified when seen. The original understanding of urban sprawl only stayed in a single spatial expansion theory. In recent years, people are beginning to find that the rational pursuit for simple economic benefits will lead to a kind of greedy urban sprawl. Some scholars believe that the essence of urban sprawl is excessive and pathological urbanization[9-11]. Urban sprawl is a phenomenon in the process of urbanization in China, and the weak ability of resource agglomeration aggravates the problem of urban sprawl in China. Urban sprawl in China is a spatial growth model with low density, low efficiency, discontinuity, large land consumption and single land use in the process of urbanization[12].

The main goal of the paper is to simulate the effects of urban's ecological consumption preference behavior on forest conservation. According to the preference choice, the sustainable urban development and management strategies are defined by calculating the cost and benefit.

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1 A simplified model

1.1 Urban sprawl

This study assumes that forest decline is only caused by urban sprawl. The forest space is modeled by a finite two-dimensional discrete square grid. The area of each grid is normalized to 1. The central location grid defines an initial city whose scale is 1. As shown in Fig. 1, it simply assumes that the city will be expanding on average to its adjacent forest grid each year, until the city expands to encroach on the boundary of the forest space. In each year $t = 1, 2, \cdots$, and time is discrete. The coordinate systems of the four directions of the forest space are consistent in Fig. 2.

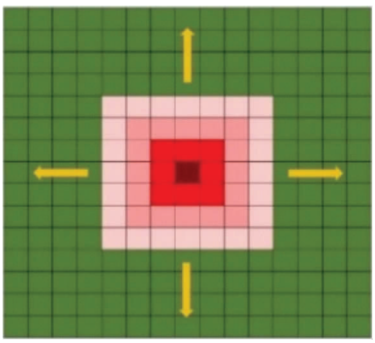

Fig. 1 Forest grid space

x	x	x	x	x	x	x	x	x	x	x
x	…	…	…	…	…	…	…	…	…	x
x	…	3	3	3	3	3	3	3	…	x
x	…	3	2	2	2	2	2	3	…	x
x	…	3	2	1	1	1	2	3	…	x
x	…	3	2	1	0	1	2	3	…	x
x	…	3	2	1	1	1	2	3	…	x
x	…	3	2	2	2	2	2	3	…	x
x	…	3	3	3	3	3	3	3	…	x
x	…	…	…	…	…	…	…	…	…	x
x	x	x	x	x	x	x	x	x	x	x

Fig. 2 Forest coordinate systems

Because population agglomeration and industrial agglomeration force the city to develop more land resources, the limited forest space around the city will be continuously eroded. If the city does not spread each year in order to protect the existing forest grid, then the city will have to be responsible for the cost of the lack of land for population growth and industrial development. For accommodating redundant population and capital elements, the city will form higher land density, which will drive the soaring price of urban land, and generate corresponding costs $c_{N,d}$ that is defined for the cost of urban sprawl control each year. The first subscript N represents the total number of existing forest grids, and the second subscript d represents the distance between each forest grid and the city grid. $c = \sum_{d=1}^{N} c_{N,d}$ is used to be expressed as the total of urban sprawl control. It can be understood that the more forest grids a city has, the greater the total cost of urban sprawl control will be. At the same time, the closer the forest grid is to the city, the more vulnerable it is to the external damage of human social and economic behaviors, so the cost of urban sprawl control is higher.

1.2 Forest benefit

Every year, if urban sprawl control is successful, the city gets revenue from each forest grid, which is normalized to unity throughout this paper. However, if urban sprawl control is unsuccessful, the city will invade around the frontier forest grid, and the forest grid will disappear forever. Other forest grids that are not on the frontier are still safe, and will bring benefits to the city as usual, but their distance from the city has been decreased by one, represented by $d - 1$. The next year, the extended city continues to invade outward around the next circle adjacent forest grids.

1.3 Discount factor

Cities have different preferences for soil and water conservation in their surrounding forests. Some cities are concerned more about current consumption, and some are concerned more about intertemporal consumption. Therefore, this paper introduces a time discount factor ω, where $0 \leqslant \omega \leqslant 1$. when $\omega = 0$, that means the city is only focused on current consumption. When $\omega = 1$, that means the city cares about consumption of all years equally. By the infinite series $\sum_{t=1}^{\infty} \omega^{t-1} = \frac{1}{1-\omega}$, one can judge how long the city will focus on forest benefits in the future. For instance, while $\omega = 0.5$, this means the city cares about on average the next two years of forest benefits.

1.4 Difficult parameter of urban sprawl control

1.4.1 Parameter definition

The representation of 'Chinese style' urban sprawl is reflected in the dual background of institutional reform and economic transformation, land urbanization is faster than population urbanization[13-15].

Boundary expansion of cities should be effectively controlled. Measurement and evaluation of urban sprawl control is the basic content. The calculation of urban sprawl parameter can be divided into single index method and multi-index method according to different measuring emphases. O'Sullivan[16] created the urban sprawl *SI* index. The specific meaning of the *SI* index is the elasticity of urban built-up area to the urban population to represent urban sprawl. This index has been widely recognized by the academic community, such as Hasse[17], Lopez[18], who extended their researches on the *SI* index. The difficulty parameter of urban sprawl control *k* introduced in this paper is reciprocal with the *SI* index. Specific calculation method of *SI* index is as follows:

$$SI = \frac{\frac{B_j - B_i}{B_i}}{\frac{P_j - P_i}{P_i}} \quad (1)$$

where, p_j represents the total population of the city at the end of year j, p_i represents the total population of the city at the end of the base year i, B_j represents the urban land area in year j, B_i represents the urban land area in year i.

If $SI \leqslant 1$, that means that urban sprawl is easier to control. If $SI > 1$, that means that urban sprawl is hardly controlled.

1.4.2 The impact of regional human capital on urban sprawl

The interaction between the level of human capital agglomeration and urban sprawl control determines the agglomeration capacity of urban resources, which is the key to judge whether the forest resources around the city are encroached or not. Li et al.[19] measured the level of human capital with the indicators of higher education and secondary education, and constructed a mathematical model affected by urban sprawl. Citing the panel data of 35 large and medium-sized cities in China from 2010 to 2014, Wang et al.[20] concluded that the regional human capital stock formed by higher education and secondary education played a positive role controlling urban sprawl and development through empirical analysis. Li et al.[21] proved that the human capital stock formed by a large number of employed people in industry and service industry was an important factor to curb urban sprawl. At the same time, the stock of human capital between cities must be differentiated, and the spatial migration of labor force and the decision of enterprise site selection will be decisively affected by the human capital status of cities[22,23].

1.4.3 Parameter econometric model

Based on Refs [24-26], this study established a cross-sectional data econometric model, taking regional human capital stock as a key explanatory variable, and industrial gross output value increment and population density as auxiliary explanatory variables:

$$k_{i,t} = \beta_0 + \beta_1 \times \ln hc_{i,t} + \beta_2 \times \ln industry_{i,t} + \beta_3 \times \ln pd_{i,t} + u_{i,t} \quad (2)$$

where $k_{i,t}$ represents the control difficulty coefficient of region i in year t; $\ln hc_{i,t}$ represents the logarithmic human capital stock of region i in year t; $\ln industry_{i,t}$ represents the logarithmic increment of industrial gross output of region i in year t; $\ln pd_{i,t}$ represents the logarithmic urban land population density of region i in year t; $u_{i,t}$ stands for the interference term of other factors; $\beta_0, \beta_1, \beta_2, \beta_3$ are coefficient terms.

As a key explanatory variable in the model, human capital stock requires some explanation. Because of the influence of many subjective and objective variables, accurate calculation of human capital is still a world-class problem. At present, general methods for human capital estimation are divided into three categories: comparative input method, education years method and income method. The comparative input method is simple to operate, but the calculation result is deviated greatly, because the national fiscal expenditure data is easy to obtain, but the individual micro data is difficult to measure. At the same time, it is difficult to determine the basic value and depreciation of educational input stock when using the perpetual inventory method. Although education years method is relatively accurate, the available data are limited, such as the existence of inter-temporal problem and the inability to estimate talent mobility. In the model, the calculation results of Zhi et al.[27] were directly used in the estimation of human capital stock. The author assumed a constant return to scale production function, introduced material capital stock, human capital stock and a comprehensive institutional variable contained in gun observable, and increased the flexible setting of material capital and human capital. The calculation results of inter-provincial human capital stock estimation in China are obtained by using correction panel data.

1.4.4 Data collection

The original data are from the China statistical yearbook on environment for 2008 and China city statistical yearbook for 2008. In this work, logarithmic processing is done for all data to make the explanatory variables closer to the normal distribution and reduce the influence of heteroscedasticity.

This model mainly analyzes the relationship between regional human capital stock factors and urban sprawl. In Table 1, $R^2 = 0.304$ and adjust $R^2 = 0.209$ are shown, which indicates that the explanatory variables selected by the model in this paper have a certain interpretation of the dependent variables. However, urban sprawl is a comprehensive issue. It is also affected by many other social and economic factors, such as geographic space structure, agricultural demand, industry development, transport networks, planning policy, globalization, demographic composition and so on. DW Test is close to 2, indicating that there is no sequence autocorrelation problem in the model (Table 2). While $F = 3.198$ and $Sig = 0.043 < 0.05$, the results are statistically significant. VIF indicates that there is no collinearity problem among each explanatory variable.

Table 1 Coefficients results

Explanatory variables	Model			
	Coefficient estimation	*t*	*Sig*	*VIF*
$\ln hc_{i,t}$	1.327	2.135	0.044	1.616
$\ln industry_{i,t}$	-0.756	-1.751	0.094	1.687
$\ln pd_{i,t}$	1.831	1.703	0.103	1.065

Table 2 Model summary and ANOVA results

Model					
R	R^2	adjusted R^2	DW	F	Sig
0.551	0.304	0.209	2.193	3.198	0.043

The results of the econometric model are

$$k = -14.234 + 1.327 \times \ln hc_{i,t} - 0.756 \times \ln industry_{i,t} + 1.831 \times \ln pd_{i,t} + u_{i,t} \quad (3)$$

From Eq. (3), $\beta_1 = 1.327$ reveals the difficulty coefficient of urban sprawl control increases with regional human capital stock, which means the urban sprawl is easier to control. The agglomeration effect of regional human capital restrains the urban sprawl.

1.4.5 Urban sprawl spatial features and regional human capital

The study was further extended to provincial and municipal areas in China, as shown in Fig. 3. Generally, the areas with better urban sprawl control are generally

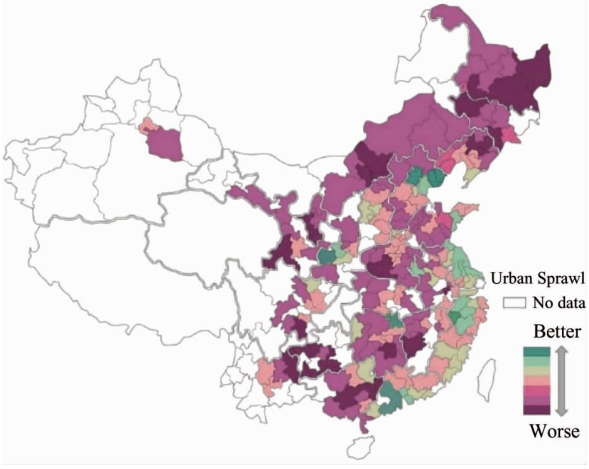

Fig. 3 Spatial features of urban sprawl

accompanied by a higher level of regional human capital, which can be interpreted as a higher level of regional human capital to enhance the local agglomeration effect, higher clustering corresponding to curb the trend of urban sprawl.

1.5 Difficult parameter of urban sprawl control

In this paper, a successful probability function of urban sprawl control is defined as $F(c)$, shown in Eq. (4). This paper assumes the function is incremented, twice continuously differentiable, and $F''(c) < 0$ is marginal decline. If $F(0) = 0$, then the city prefers to continue to expand without restriction, regardless of forest conservation. The probability of success in forest protection (urban sprawl control) is 0. If $\lim_{c\to\infty} F(c) = 1$, then it means that the city has made infinite efforts to protect the forest space, bearing the unlimited cost of urban sprawl control. The probability of success in forest protection (urban sprawl control) is 1.

$$F(c) = \frac{k \times c}{1 + k \times c}, \text{ and } k > 0 \quad (4)$$

Fig. 4 shows a graph of the probability function for different values of k.

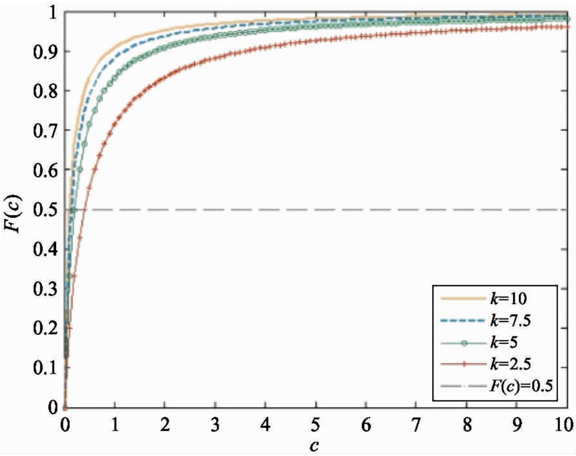

Fig. 4 Probability function $F(c)$ ($c \in [0,10]$)

First derivative of $F(c)$ is

$$F'(c) = \frac{k}{(1 + k \times c)} - \frac{k^2 \times c}{(1 + k \times c)^2} \quad (5)$$

From Eq. (5), when $c = 0$, $F'(0) = k$, the greater k value is, the higher the likelihood of successful urban sprawl control is and the lower the difficulty is.

2 Nash equilibrium strategy for forest conservation

A forest grid i is located at a certain circle of the forest space around the city. If the city protects forest grid i, the forest grid i will transfer a control cost to the city, control cost is recorded as c_{N,d_i}. In year $t = 1$, the city is located in the initial position, $x = 0$. Note that if the city succeeds at forest conservation (No urban sprawl for the first year), in year $t = 2$, the city will face the same situation. On the contrary, if the city can't succeed at forest conservation, then a circle of forest grids located $x = 1$ are invaded by urban sprawl for the first year. In year $t = 2$, the forest grid i will face the situation: total number of remaining forest grids in the entire forest space is $N' = [N - (1 + 2 \times 1)^2]$, and the forest grid i' distance from the city decreases to $d_i - 1$. Similar reasoning applies to the situation that more than one circle forest grids are invaded. When m circles forest grids are invaded, forest grid i will face the situation as: total number of remaining forest grids in the entire forest space is $N' = [N - (1 + 2 \times m)^2]$, and the forest grid i' distance from the city decreases to $d_i - m$.

The strategy vector of the forest grid i is a d_i-tuple:

$$c_{N,d_i} = (c_{N,d_i}, c_{[N-(1+2\times1)^2],d_i-1}, \cdots, c_{[N-(1+(d_i-1)\times2)^2,1]})$$
$$1 \leqslant d_i \leqslant \frac{\sqrt{N+1}-1}{2} \tag{6}$$

When the total number of forest grids around the city is N, a set of strategies of all forest grids for the city, $\{c^*_{N,1}, \cdots, c^*_{N,\frac{\sqrt{N+1}-1}{2}}\}$ is a Nash equilibrium strategy profile, which means that in the implementation of the equilibrium strategy, the speculative behavior of urban forest grid destruction is avoided.

Eq. (7) suggests that there is a Nash equilibrium strategy for each forest grid i.

$$R_{N,d_i}(c^*_{N,1}, \cdots, c^*_{N,d_i-1}, c^*_{N,d_i}, c^*_{N,d_i+1}, \cdots, c^*_{N,\frac{\sqrt{N+1}-1}{2}})$$
$$\geqslant R_{N,d_i}(c^*_{N,1}, \cdots, c^*_{N,d_i-1}, c_{N,d_i}, c^*_{N,d_i+1}, \cdots, c^*_{N,\frac{\sqrt{N+1}-1}{2}}) \tag{7}$$

where, R_{N,d_i} represents the benefits of forest grid i to the city.

3 Results and discussion

3.1 One circle of forest grids case

As shown in Fig. 5, each forest grid gets revenue and takes cost $\begin{cases} c = c_{1,1} \\ R = R_{1,1} \end{cases}$

When $t = 1$, if urban sprawl control is successful, then the city will face the same situation on forest space for the second year.

Revenue for each forest grid 1 is shown in Eq. (8).

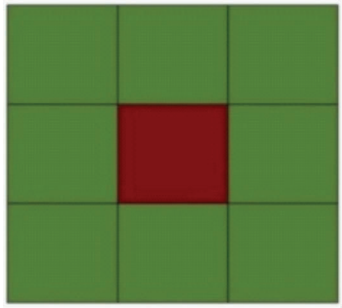

Fig. 5 One circle of forest grids case

$$R(c) = F(c) \times (1 + \omega \times R(c)) - c = \frac{F(c) - c}{1 - \omega \times F(c)} \tag{8}$$

As $F(c) = \frac{k \times c}{1 + k \times c}$, Eq. (9) and Eq. (10) can be obtained:

$$R(c) = \frac{\frac{k \times c}{1 + k \times c} - c}{1 - \omega \times \frac{k \times c}{1 + k \times c}} \tag{9}$$

$$R'(c) = \frac{\left(\frac{k}{1 + k \times c} - \frac{k^2 \times c}{(1 + k \times c)^2 - 1}\right)}{\left(\frac{1 - \omega \times k \times c}{(1 + k \times c)}\right)} - \frac{\left(\frac{k \times c}{(1 + k \times c)} - c\right)}{\left(1 - \frac{\omega \times k \times c}{(1 + k \times c)}\right)^2 \times \left(\frac{-\omega \times k}{(1 + k \times c)} + \frac{\omega \times k^2 \times c}{(1 + k \times c)^2}\right)} \tag{10}$$

(1) For $\omega = 1$, $k > 1$ with Eq. (11).

$$\begin{cases} c^*_{1,1} = \frac{k-1}{2 \times k} \\ R^*_{1,1} = \frac{(k-1)^2}{4 \times k} \end{cases} \tag{11}$$

Further calculations can be made, for example.

Assuming the difficulty coefficient of urban sprawl control $k = 7$, the following can be further calculated:

Conservation and control cost on forest grid 1 is $c^*_{1,1} = \frac{k-1}{2 \times k} = \frac{3}{7}$.

Total cost on the first circle of forest grids is $\frac{3}{7} \times 8 = \frac{24}{7}$.

Revenue on forest grid 1 is $R^*_{1,1} = \frac{(k-1)^2}{4 \times k} = \frac{3}{2}$.

Total revenue on the first circle of forest grids is $\frac{3}{2} \times 8 = 12$.

As $F(c) = \frac{k \times c}{1 + k \times c}$, $F(c_{1,1}^*) = \frac{k-1}{1+k}$ can be obtained.

Forest conservation success probability is 75%, forest conservation is sustained on average for 3 years.

Therefore,

Total control cost of urban sprawl is $\frac{24}{7} \times 3 = \frac{72}{7}$.

Total forest revenue is $12 \times 3 = 36$.

Total profit of urban is $36 - \frac{72}{7} = 25\frac{5}{7}$.

(2) For $\omega < 1$, with Eq. (12).

$$\begin{cases} c_{1,1}^* = \begin{cases} 0 & k \leqslant 1 \\ \frac{\sqrt{(1-\omega) \times k - \omega} - 1}{(1-\omega) \times k} & k > 1 \end{cases} \\ R_{1,1}^* = \begin{cases} 0 & k \leqslant 1 \\ \frac{1 + \omega + k - \omega \times k - 2 \times \sqrt{(1-\omega) \times k + \omega}}{(1-\omega)^2 \times k} & k > 1 \end{cases} \end{cases} \tag{12}$$

For $k > 1$, the cost $c_{1,1}^*$ for forest grid 1 increases with discount factor ω, this means that the city is more inclined to protect forest and bear higher urban sprawl control cost.

Further calculations can be made, for example:

Assuming the difficulty coefficient of urban sprawl control $k = 8$ and discount factor $\omega = 0.75$ with Eq. (13).

$$\begin{cases} c_{1,1}^* = \frac{\sqrt{(1-\omega) \times k - \omega} - 1}{(1-\omega) \times k} = 0.06 \\ R_{1,1}^* = \frac{1 + \omega + k - \omega \times k - 2 \times \sqrt{(1-\omega) \times k + \omega}}{(1-\omega)^2 \times k} = 0.86 \end{cases} \tag{13}$$

Total cost on the first circle of forest grids is $0.06 \times 8 = 0.48$.

Total revenue on the first circle of forest grids is $0.86 \times 8 = 6.88$.

Forest conservation success probability is 75%, forest conservation is sustained on average for 3 years.

Therefore,

Total control cost of urban sprawl is $0.48 \times 3 = 1.44$.

Total forest revenue is $6.88 \times 3 = 20.64$.

Total profit of urban is $20.64 - 1.44 = 19.2$.

For $k \leqslant 1$, it is very difficult for the city to protect forest, as a result, the city will continue to encroach on forest land, both forest cost and forest revenue are zero.

3.2 Multiple-circles of forest grids case

Similar reasoning applies to the situation that more than one circle forest grids are invaded.

For $t = 1$, if urban sprawl control is successful, then in year $t = 2$, the city will face the same situation on forest space for the second year.

Revenue for each forest grid 1 is shown in Eq. (14).

$$\begin{aligned} & R_{\frac{\sqrt{N+1}-1}{2},1}\left(c_{\frac{\sqrt{N+1}-1}{2},1},\ c^*_{\frac{\sqrt{N+1}-1}{2},2},\cdots,c^*_{\frac{\sqrt{N+1}-1}{2},\frac{\sqrt{N+1}-1}{2}}\right) \\ &= F\left(c_{\frac{\sqrt{N+1}-1}{2},1} + \sum_{d_j \neq 1} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\right) \times \left(1 + \omega \times R_{\frac{\sqrt{N+1}-1}{2},1}\right) \\ &\quad - c_{\frac{\sqrt{N+1}-1}{2},1} \\ &= \frac{F\left(c_{\frac{\sqrt{N+1}-1}{2},1} + \sum_{d_j \neq 1} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\right) - c_{\frac{\sqrt{N+1}-1}{2},1}}{1 - \omega \times F\left(c_{\frac{\sqrt{N+1}-1}{2},1} + \sum_{d_j \neq 1} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\right)} \end{aligned} \tag{14}$$

Differentiating Eq. (14) with respect to $c_{\frac{\sqrt{N+1}-1}{2},1} > 0$, the solution is

$$\begin{aligned} & R'_{\frac{\sqrt{N+1}-1}{2},1}\left(c_{\frac{\sqrt{N+1}-1}{2},1},\ c^*_{\frac{\sqrt{N+1}-1}{2},2},\cdots,c^*_{\frac{\sqrt{N+1}-1}{2},\frac{\sqrt{N+1}-1}{2}}\right) \\ &= -1 + \omega \times F\left(c_{\frac{\sqrt{N+1}-1}{2},1} + \sum_{d_j \neq 1} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\right) \\ &\quad + \left(1 - \omega \times c_{\frac{\sqrt{N+1}-1}{2},1}\right) \times F'\left(c_{\frac{\sqrt{N+1}-1}{2},1} + \sum_{d_j \neq 1} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\right) \end{aligned} \tag{15}$$

For $t = 1$, if urban sprawl control is unsuccessful, then revenue for each forest grid 1 is shown in Eq. (16).

$$\begin{aligned} & R_{\frac{\sqrt{N+1}-1}{2},d_i}\left(c_{\frac{\sqrt{N+1}-1}{2},1},c^*_{\frac{\sqrt{N+1}-1}{2},2},\cdots,c^*_{\frac{\sqrt{N+1}-1}{2},d_i},\cdots,c^*_{\frac{\sqrt{N+1}-1}{2},\frac{\sqrt{N+1}-1}{2}}\right) \\ &= F\left(c_{\frac{\sqrt{N+1}-1}{2},i} + \sum_{d_j \neq d_i} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\right) \times \left(1 + \omega \times R_{\frac{\sqrt{N+1}-1}{2},d_i}\right) + \left(1 - F\left(c_{\frac{\sqrt{N+1}-1}{2},i} + \sum_{d_j \neq d_i} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\right)\right) \times \left(1 + \omega \times R^*_{\frac{\sqrt{N+1}-1}{2}-1,d_i-1}\right) \\ &\quad - c_{\frac{\sqrt{N+1}-1}{2},d_i} \\ &= \frac{1 - c_{\frac{\sqrt{N+1}-1}{2},d_i} + \omega \times R^*_{\frac{\sqrt{N+1}-1}{2}-1,d_i-1} \times \left(1 - F\left(c_{\frac{\sqrt{N+1}-1}{2},d_i} + \sum_{d_j \neq d_i} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\right)\right)}{1 - \omega \times F\left(c_{\frac{\sqrt{N+1}-1}{2},d_i} + \sum_{d_j \neq d_i} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\right)} \end{aligned} \tag{16}$$

Differentiating Eq. (16) with respect to $c_{N,1} > 0$, the solution is shown in Eq. (17).

$$R_{\frac{\sqrt{N+1}-1}{2},d_i'}\left(c_{\frac{\sqrt{N+1}-1}{2},1},\ c^*_{\frac{\sqrt{N+1}-1}{2},2},\cdots,c^*_{\frac{\sqrt{N+1}-1}{2},d_i},\cdots,c^*_{\frac{\sqrt{N+1}-1}{2},\frac{\sqrt{N+1}-1}{2}}\right)$$

$$= -1 + \omega^{t-1} \times F\Big(c_{\frac{\sqrt{N+1}-1}{2},d_i} + \sum_{d_j\neq d_i} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\Big) + \Big(1 - \omega \times c_{\frac{\sqrt{N+1}-1}{2},d_i} - \omega \times R^*_{\frac{\sqrt{N+1}-1}{2}-1,\, d_i-1} + \omega^2 \times R^*_{\frac{\sqrt{N+1}-1}{2}-1,\, d_i-1} \times F'\Big(c_{\frac{\sqrt{N+1}-1}{2},\, d_i} + \sum_{d_j\neq d_i} c^*_{\frac{\sqrt{N+1}-1}{2},d_j}\Big) \tag{17}$$

To solve the Nash equilibrium of forest space, it has Eq. (18):

$$\begin{cases} R'_{\frac{\sqrt{N+1}-1}{2},1}\Big(c_{\frac{\sqrt{N+1}-1}{2},1},\ c^*_{\frac{\sqrt{N+1}-1}{2},2},\ \cdots,\ c^*_{\frac{\sqrt{N+1}-1}{2},\frac{\sqrt{N+1}-1}{2}}\Big) = 0 \\ R_{\frac{\sqrt{N+1}-1}{2},\, d_i'}\Big(c_{\frac{\sqrt{N+1}-1}{2},1},\ c^*_{\frac{\sqrt{N+1}-1}{2},2},\ \cdots,\ c^*_{\frac{\sqrt{N+1}-1}{2},\, d_i},\ \cdots,\ c^*_{\frac{\sqrt{N+1}-1}{2},\frac{\sqrt{N+1}-1}{2}}\Big) = 0 \end{cases} \tag{18}$$

For $\omega = 1$, $c^*_{\frac{\sqrt{N+1}-1}{2},\, d_i} = 1 + \dfrac{F\Big(c_{\frac{\sqrt{N+1}-1}{2},\, d_i} + \sum_{d_j\neq d_i} c^*_{\frac{\sqrt{N+1}-1}{2},\, d_j}\Big) - 1}{F'\Big(c_{\frac{\sqrt{N+1}-1}{2},\, d_i} + \sum_{d_j\neq d_i} c^*_{\frac{\sqrt{N+1}-1}{2},\, d_j}\Big)}$ is constant, the solution is shown in Eq. (19).

$$c^*_{\frac{\sqrt{N+1}-1}{2},1} = c^*_{\frac{\sqrt{N+1}-1}{2},\,2} = \cdots = c^*_{\frac{\sqrt{N+1}-1}{2},\, d_i} = \cdots = c^*_{\frac{\sqrt{N+1}-1}{2},\, \frac{\sqrt{N+1}-1}{2}} = \frac{k-1}{k \times \Big(\frac{\sqrt{N+1}+1}{2}\Big)} \tag{19}$$

For $\omega < 1$, it has Eq. (20).

$$\begin{cases} c_{\frac{\sqrt{N+1}-1}{2},1} = \dfrac{\sqrt{\omega + k - k\times\omega + k\times\omega\times(1-\omega)\times\sum_{d_j\neq 1} c^*_{\frac{\sqrt{N+1}-1}{2},\, d_j}} - 1}{(1-\omega)\times k} - \sum_{d_j\neq 1} c^*_{\frac{\sqrt{N+1}-1}{2},\, d_j} \\ c_{\frac{\sqrt{N+1}-1}{2},\, d_i} = \dfrac{\sqrt{\omega + k\times\omega - k\times\omega^2 - R^*_{\frac{\sqrt{N+1}-1}{2}-1,\, d_i-1}\times\omega\times(1-\omega)^2\times k + k\times\omega\times(1-\omega)\times\sum_{d_j\neq d_i} c^*_{\frac{\sqrt{N+1}-1}{2},\, d_j}} - 1}{(1-\omega)\times k} - \sum_{d_j\neq d_i} c^*_{\frac{\sqrt{N+1}-1}{2},\, d_j} \end{cases} \tag{20}$$

Simultaneous equations are solved by Eq. (21) and Eq. (22).

$$c^*_{\frac{\sqrt{N+1}-1}{2},1} = \Big[-2\times\frac{\sqrt{N+1}-1}{2}\times\omega + \Big(\frac{\sqrt{N+1}-3}{2}\Big)\times\omega^2 + 2\times k\times\frac{\sqrt{N+1}-1}{2}\times(1-\omega)^2\times\Big(\frac{\sqrt{N+1}-3}{2} + \omega\times\sum_{d_i=1}^{\frac{\sqrt{N+1}-3}{2}} R^*_{\frac{\sqrt{N+1}-3}{2},\, d_i}\Big) + \omega\times \sqrt{4\times\frac{\sqrt{N+1}-1}{2}\times\omega + 4\times\Big(\frac{\sqrt{N+1}-1}{2}\Big)^2\times k\times(1-\omega) + \Big(\frac{\sqrt{N+1}-3}{2}\Big)^2\times\omega^2 + 4\times\frac{\sqrt{N+1}-1}{2}\times k\times(1-\omega)^2\times\Big(1-\omega\times\sum_{d_i=1}^{\frac{\sqrt{N+1}-3}{2}} R^*_{\frac{\sqrt{N+1}-3}{2},\, d_i}\Big)}\Big] \div \Big(2\times k\times\Big(\frac{\sqrt{N+1}-1}{2}\Big)^2\times\omega\times(1-\omega)\Big) \tag{21}$$

$$c^*_{\frac{\sqrt{N+1}-1}{2},\, d_i} = \Big[-2\times\frac{\sqrt{N+1}-1}{2}\times\omega + \Big(\frac{\sqrt{N+1}-3}{2}\Big)\times\omega^2 - 2\times k\times\frac{\sqrt{N+1}-1}{2}\times(1-\omega)^2\times\Big(1 + \frac{\sqrt{N+1}-1}{2}\times\omega\times R^*_{\frac{\sqrt{N+1}-3}{2},\, d_i-1} - \omega\times\sum_{d_j=1}^{\frac{\sqrt{N+1}-3}{2}} R^*_{\frac{\sqrt{N+1}-3}{2},\, d_j}\Big) + \omega\times \sqrt{4\times\frac{\sqrt{N+1}-1}{2}\times\omega + 4\times\Big(\frac{\sqrt{N+1}-1}{2}\Big)^2\times k\times(1-\omega) + \Big(\frac{\sqrt{N+1}-3}{2}\Big)^2\times\omega^2 + 4\times\frac{\sqrt{N+1}-1}{2}\times k\times(1-\omega)^2\times\Big(1-\omega\times\sum_{d_j=1}^{\frac{\sqrt{N+1}-3}{2}} R^*_{\frac{\sqrt{N+1}-3}{2},\, d_j}\Big)}\Big] \div \Big(2\times k\times\Big(\frac{\sqrt{N+1}-1}{2}\Big)^2\times\omega\times(1-\omega)\Big) \tag{22}$$

4 The choice of discount factor for forest conservation

As shown in Fig. 6, this paper simulates that the city has 2 circles of forest grids case: when the city faces different levels of urban sprawl control, this city chooses different time preference discount factor of forest conservation. Under the constraint of Nash equilibrium strategy, the cost differentiation of the first circle of forest grids and the second circle of forest grids is formed.

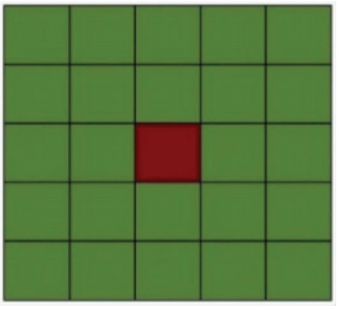

Fig. 6 Two circles of forest grids case

In this paper, the cost curve is plotted by Fig. 7, showing that there is a discount factor threshold for the forest grids cost payment of different urban circles. If $k = 3$, then $\omega = 0.8$, and it also means that the city is focused on forest conservation for the next five years. When the discount factor of time preference of city selection is lower than 0.8, the rational strategy is to pay only the cost of the first circle of forest grids. If the city pays more attention to protecting the forest environment in the future, the cost of the first circle of forest grids paid by the city will increase as the time preference discount increases with a significant change at the threshold of 0.8. Leading to a significant change in that threshold value of 0.8, which means that the city's ideal strategy is to pay the cost for the two circles of forest together. This paper can see immediately that above the threshold the cost level for the second circle of forest grids increases with discount factor, while the cost level for the first circle of forest grids decreases with discount factor, which indicates that there is spatial spillover in forest conservation, and a good forest ecological environment will have an optimized impact on the surrounding environment and co-evolve into a regional organic ecosphere. For $k = 10$, it can get similar results. However, there is one difference. When the difficulty of urban sprawl control is reduced, it means that the scale of urban development is more reasonable, the population and industries accumulated by the agglomeration effect are more ecologically resilient, and the control cost paid is correspondingly lower and the threshold value is higher. If $k = 10$, then $\omega = 0.86$, it also means the city focuses on forest conservation for the next seven years. Compared with the great difficulty in expansion control, the cost curve at this time is relatively flat at the initial stage and steep at the later stage. When approaching the threshold value, the cost curve will show a sharp angle, and more control cost of the city will be paid.

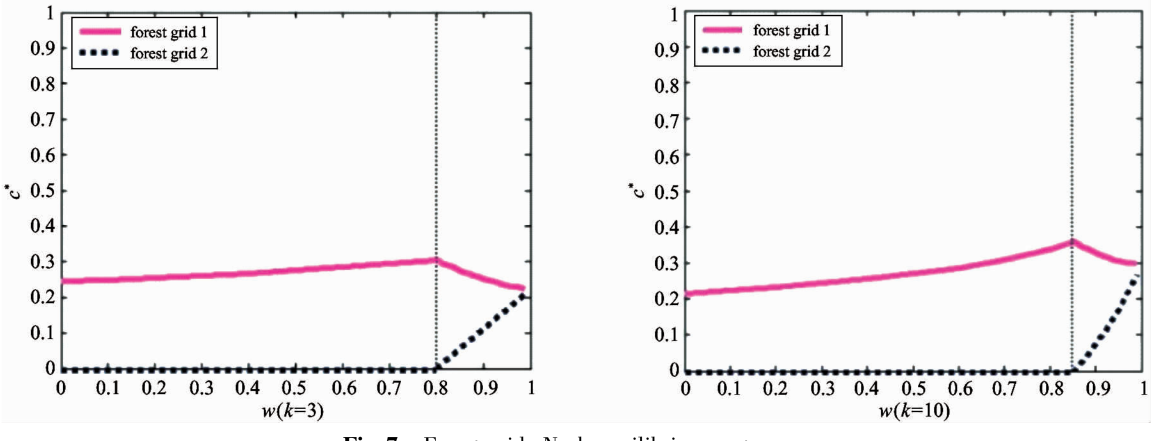

Fig. 7 Forest grids Nash equilibrium cost curve

5 Conclusions

The empirical analysis in this paper verified the negative correlation between regional human capital level and urban sprawl. The forest conservation model simulated the encroachment of urban sprawl on surrounding forest space. Through the calculation of one-circle forest grids and multi-circles forest grids, this study quantified the thresholds that cities face when facing with different forest conservation time preferences, and analyzed the impact of selecting different urban sprawl control difficulty parameter and discount factor on the payment cost of forest conservation under Nash equilibrium strategy. For example, it calculated the benefits and costs of forest conservation.

At present, China's urban development is driven by gross domestic product (GDP), one-sided pursuit of short-term economic benefits, ignoring the bearing capacity of urban resources, and the lack of sustainable development concept of intergenerational equity. Residential suburbanization, population and income growth, sharp decline in transportation costs, institutional deficiencies and local government misconduct are the main factors affecting urban sprawl in China. If regional human capital can play a positive role, it will help to control urban sprawl. Large cities should give full play to the advantages of agglomeration economy, promote job-housing matching. By implementing shrewd contraction, they can avoid the formation of migratory bird urban population flow. Small and medium-sized cities should strengthen the ability to resources agglomeration, make use of the environmental resources of small and medium-sized cities with comparative advantages to develop supporting industries, improve local employment, and strictly control the inefficient urban sprawl mode of concentric circle.

The concept of balanced development between urban economy and forest conservation should be established, and the harmonious ecological civilization between human and nature, economy and environment, human and society should be constructed. In addition, forming sustainable ecological consumption preference behavior is an effective way to solve the disorder urban sprawl.

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