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The impact of environmental taxation on the structure and performance of industrial symbiosis networks: An agent-based simulation study

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ABSTRACT

How to use appropriate policy measures to intervene industrial symbiosis is valuable in theory but still lacks exploration. This paper discusses the effect of environmental taxation on industrial symbiosis networks. Firstly, the formation mechanism of industrial symbiotic network is analysed with the idea of agent-based modelling. Then, a simulation model was built to simulate the emergence process of industrial symbiosis networks. On this basis, the influence of environmental taxation on the structure and performance of the industrial symbiosis networks is explored. The results show that when the intensity of environmental tax is low, the industrial symbiotic network has the structural characteristics of random network. With the increase of environmental tax intensity, the cyclic ordering of network structure is gradually enhanced. The collection of environmental tax will not only reduce pollution, but also reduce the economic output of the network and reduce enterprise income to a greater extent. Finally, some relevant suggestions for the government to formulate environmental tax policy are provided based on the results.

1. Introduction

There always exists a certain degree of contradiction between economic development and ecological environment. Both developed and developing countries are confronted with this contradiction in the process of industrialization. The rapid development of industry caused the rapid depletion of resources, serious environmental pollution, and ecosystem imbalance. It is particularly important to find a new way for the coordinated development of ecology and economy for industrial activities. Many countries have gone through the old path of "treatment after pollution", while some other countries are striving to strike a balance between the two and constantly seeking effective ways to resolve this contradiction.

One area of research addressing this problem is industrial ecology. Industrial ecology marks a shift in the control of industrial pollution from "terminal control" to planning a more environmentally friendly overall strategy for industrial development [1]. Among the numerous measures for industrial ecological development, industrial symbiosis [2] is an important pattern. Frosch and Gallopoulus [3] pointed out that the industrial system could simulate the interaction of biological populations in nature, carry out the industrial symbiosis of mutual utilization of resources among enterprises, and then establish a symbiosis network aiming at win-win situation of economy and environment. In industrial symbiosis, the waste produced by one enterprise can be used as input in the production process by other enterprises [4], which can not only bring more economic benefits to relevant enterprises, but also provide environmental and social benefits for the whole economy [5]. The network connected by such symbiotic relationship is called an industrial

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symbiotic network [6]. Enterprises in the industrial symbiosis networks usually belong to several different industries, which makes the industrial symbiosis networks cross-industry cooperation mode higher than the traditional supply chain level [7].

Based on years of practice in the field of industrial ecology, scholars have conducted in-depth studies on the existence basis [8], construction methods [9], characteristics [10], and other aspects of industrial symbiosis networks, which provides a useful reference for guiding industrial ecological practice. However, at the same time, it is also found that the industrial symbiotic network has a fragile side in practice [11]. From the internal perspective of industrial symbiosis network, the high dependence between enterprises leads to the increase of business risk and internal diseconomies, the solidified cooperation mode hinders enterprise innovation, and the construction of high barriers [12]. If not solved properly, the industrial symbiosis network will operate inefficiently or even disintegrate. From the external perspective of industrial symbiosis network, its emergence and development are greatly influenced by the external environment. Under the influence of economic factors such as the law of value and market mechanisms, industrial symbiosis is sometimes difficult to emerge [13]. Therefore, it is necessary for the government to adopt appropriate policy tools to adjust the industrial symbiotic relationship to improve the vitality and adaptability of the industrial symbiotic network.

Public is an effective tool to adjust industrial activities [14]. To adjust the industrial symbiosis relationship, the government can adopt two kinds of policy tools: regulation and guidance. Regulatory tools and guidance tools, respectively, force or guide enterprises to voluntarily find other methods to dispose of waste by punishing the discharge of waste and rewarding the emission reduction of enterprises [15]. The corresponding economic instruments include environmental taxation [16], economic compensation [17], investment in infrastructure construction [18], transaction financing [19], etc. However, few studies have quantified the role of policy measures in the formation of industrial symbiosis networks [20]. It is insufficient to study the influence of different policy measures on the structure and performance of an industrial symbiotic networks.

In the business world, the profit-seeking goal of enterprises is usually put in the first place, and the impact on the environment is usually put secondary. For example, over the years, the development of traditional industries in China has always given the highest priority to economic benefits, thus keeping the production in a state of high input, low output and high pollution for a long time [21]. Therefore, it will encounter many difficulties for enterprises to spontaneously build industrial symbiosis systems, so the government needs to play an important role. In order to achieve effective regulation of industrial symbiosis networks, the government needs to have a deep understanding of the specific mechanism of the effect of the adopted policies and measures. However, this area is understudied for several reasons. First, the incidence of industrial symbiosis is relatively low due to the spontaneous occurrence of industrial symbiosis in reality is affected by many factors [22]. Second, data in this area is hard to access, or even doesn't exist [23]. Third, it is difficult to distinguish the influence of policy factors from other factors in theory [22]. And also, it is for these reasons that the multi-agent simulation method chosen in this study is particularly appropriate and necessary to explore this problem.

Environmental taxation [24] is one of the most important instruments among many policy measures in the generation of industrial symbiosis networks, it is a kind of compulsory tax for the prominent "manifest pollution" such as sewage, waste gas, noise and waste in order to maintain the ecological environment. Environmental Taxation is also known as ecological taxation or green taxation. It is an economic means to internalize the social costs of environmental pollution and ecological destruction into production costs and market prices, and then allocate environmental resources through the market mechanism. The environmental taxes collected in some developed countries mainly include sulphur dioxide tax, water pollution tax, noise tax, solid waste tax, and garbage tax. The goal of the tax system is usually to achieve a balanced structure of fairness and efficiency. For environmental taxation, if the intensity of collection is too weak, it will not be enough to realize the protection of the ecological environment. If the collection intensity is too strong, it will produce the distortion effect of taxation and impede the development of related industries.

A large number of literatures have shown that environmental tax plays an important role in the formation of industrial ecosystem [13,16,25,26], and the government can use such policy tools to foster an environment conducive to the spontaneous generation of industrial symbiosis and encourage enterprises to spontaneously form economically and ecologically efficient industrial symbiosis networks [16,27]. However, there is still a lack of exploration on the mechanism of this spontaneous formation process in the literature, and few studies have quantified the formation process and economic effects of policies and measures on industrial ecological networks [20]. As a result, we still lack of understanding of how environmental tax affects the structure and function of industrial symbiosis networks. Therefore, although the feasibility of industrial symbiosis networks is generally recognized in theory, the application of this method in reality is still relatively lacking [20].

This paper explores the role of environmental taxation in the formation of industrial symbiosis networks. The research question is how environmental tax affects the structure and performance of industrial symbiosis networks. First, the formation mechanism of the industrial symbiosis network is analysed with the idea of multi-agent modelling method, and a simulation model of the industrial symbiosis network is established. Then the model is run under different collection intensities of environmental taxation to observe the formation process of the industrial symbiosis network and further measure its corresponding structure and economic and ecological performance. Finally, based on the results of the model, some suggestions are provided for the government to adjust the contradiction between economic development and ecological environment through environmental taxation.

2. Formation mechanism of industrial symbiotic networks

The early industrial symbiotic network appeared in the eco-industrial parks. For example, the famous Kalundborg Eco-industrial Park [25] in Denmark contains the municipal government and five other core enterprises in different industries, namely, a power plant, an oil refinery, a gypsum plant, a biopharmaceutical plant, and a soil remediation company. Through the cooperative utilization of energy, water, and by-products, these enterprises have greatly improved the coal combustion efficiency, industrial water use and sulphur dioxide emission, and other environmental indicators in the park. After Kalundborg, many countries have adopted the method of constructing eco-industrial parks to solve the contradiction between economy and environment, and established many similar eco-industrial parks [18,26], forming industrial symbiosis networks inside industrial parks. In addition, there are also some industrial symbiosis networks spontaneously formed outside the eco-industrial park. Desrochers [27] et al. pay attention to the existence of spontaneous by-product exchange networks in cities or larger areas. For example, the exchange and cooperative utilization of waste catalysts, waste lye, and by-products such as oil sludge, slag, and iron powder among enterprises in the petrochemical industry, cement industry, paper industry and other industries in Dalian, China initially formed a by-product exchange network with certain spatial dispersion [28].

Both the top-down built industrial symbiosis network inside the industrial park and the bottom-up constructed industrial symbiosis network outside the industrial park are complex networks formed by enterprises in various forms of cooperation under the dual purpose of reducing environmental problems and promoting economic development, which are affected by many factors [29]. Enterprises represented by network nodes usually come from multiple interrelated industries, and the edges in the network represent the partnerships between these enterprises. These relationships not only include industrial symbiotic relationships such as by-product exchange and environmental resource outsourcing [30], but also include interactions in many fields such as materials, transportation, human resources, information communication, community life, energy, marketing, environmental health safety and production environment [31]. These different partnerships will interact with each other under the pressure of resource scarcity and enterprises' pursuit of profit maximization, thus leading to the formation of different structural characteristics of the industrial symbiotic networks under different conditions [32].

However, many scholars consider the self-organized approach as the most promising one, because such kind of industrial symbiosis can arise and evolve spontaneously, without any central entity managing them [33]. In particular, firms can replace production inputs with wastes and by-products of other firms or use such wastes to generates new products, which are sold in the market [22]. By establishing industrial symbiosis, firms can gain economic benefits because of enhancing production efficiency and, at the same time, create environmental benefits because replacing inputs with wastes and by-products [22,33]. Therefore, this paper divides the relationship between enterprises in industrial symbiosis networks into two categories, namely, industrial symbiosis relationship and economic relationships. Among them, industrial symbiosis relationship refers to the cooperative relationship between enterprises in the form of by-product exchange and waste utilization, which is conducive to the protection of the ecological environment. Economic relationship refers to the cooperative relationship between enterprises in the industrial symbiosis network which is purely oriented by economic benefits to improve the market competitiveness. These two kinds of relations exist in the industrial symbiosis network at the same time, and the tension between them results in the formation and development of the industrial symbiosis network. For example, in the real case study of literature [21], there are enterprises from 3 different industries forming a real industrial symbiotic network, which are the sugar industry, the alcohol industry, and the fertilizer industry. The economic relationship represents the cooperate relations between the enterprises that do not involve wastes or by-products substitutions alongside the supply chain inside each industry, such as the product of fertilizer enterprises are the input of sugar industries, where the fertilizer products are not wastes or by-products, which are meant to be discarded, or the many sugar refining plants cooperate or merge together to enhance production efficiency. While there are some industrial symbiosis relationships in this industrial symbiosis networks, such as the relationships between sugar enterprises and alcohol enterprises, as the waste of sugar industry (molasses) is the input of alcohol industry; and the relationships between alcohol enterprises and fertilizer industries, as the waste of alcohol industry (alcohol slops) is the input of fertilizer industry.

The ecological orientation reflected by industrial symbiosis relationships is the characteristic that the industrial symbiosis network is different from other social networks, and the economic orientation reflected by the economic relationship is the basis for the existence of the industrial symbiosis network. The symbiosis process of industrial symbiosis network is the process of forming a large complex network among enterprises through the formation of the above two kinds of connections.

The collection of environmental tax will increase the cost of pollution emission of enterprises, so it will promote the preference of enterprises to establish industrial symbiosis relations. Through changing the benefits of establishing different network connections of enterprises, environmental taxation makes adjustment of the relationship between subjects within the whole system, therefore producing an important impact on the structure of industrial symbiosis network and its functional performance.

3. The simulation model of industrial symbiosis network

Based on the above discussion on the formation mechanism of industrial symbiosis networks, we adopted the agent-based modelling (ABM) method [34] to construct the simulation model of industrial symbiosis networks. The ABM drives the interaction between the subjects by defining the objects, attributes, and action rules of the subjects, thus emerging the overall characteristics of the whole system [35]. Therefore, ABM can analyse the system dynamics that cannot be analysed by analytical models, so it is particularly suitable for the study of complex systems [20]. In ABMs, agents are defined by two aspects [36,37]: (1) a given set of goals and actions to be achieved; and (2) rules that drive the agents to interact with other agents and the environment. The behaviour of the system is emerging on the basis of the agents' behaviour, rather than being defined by the researcher. ABM enables researchers to anticipate the potential impacts of small behaviour changes of agents, or environmental changes from the social, natural, or economic sub-systems [23].

The feature of industrial symbiotic network is considered to have strong adaptability in resisting fluctuations in production level, symbiotic flow, participant dimension and number [38]. Previous studies have developed and used advanced tools for analysing material and energy flows and social network structures in industrial symbiosis [22,23,33,39]. The general principal of this approach is to model and simulate certain aspects of industrial symbiosis, such as creation of industrial synergies, exchange of materials, sorting and handling processes, creation and development of social connections, to anticipate the impact of some important parameters [23].

These studies have the same construction logic and similar research paradigms, only differ in research focus and model details. We also adopt the same idea here to construct the industrial symbiotic network model in this study. The model established below includes three aspects: 1) basic settings of network nodes and their properties; 2) the behaviour of network nodes and the formation rules of the network connection; and 3) running steps of the simulation process.

3.1. Basic settings of network nodes and their properties

Consider an industrial symbiosis network composed of N nodes, where each node represents an enterprise. Each node is defined as an input-output vector. For enterprise i, let the input-output vector $v_i = (I_{i,1}, \ldots I_{i,l}, O_{i,1}, O_{i,2})$. The first l dimensions of the vector v_i represents the l resources that enterprise i needs to invest in its production process, and $I_{i,l}$ represents the amount of the amount of resource l owned by enterprise i. The latter 2 dimensions of vector v_i represents the two kinds of outputs of enterprise i. Where $O_{i,1}$ represents the economic output of enterprise i, which is embodied in the income of the enterprise. $O_{i,2}$ represents the environmentally harmful by-products produced in the production process of this enterprise. By-products are non-major products produced by the same production process or by further processing wastes in production while the main products are produced by the enterprise. By-products end in two ways. Some by-products may be put into the production process as another enterprise's resources and bring some economic benefits. Others may be discharged into the environment as a waste, causing a certain degree of pollution to the environment. Since the forms and units of measurement of waste are different, we measure it from the perspective of the damage to the ecological environment and quantify the value of $O_{i,2}$ as the cost of the treatments that makes the by-product harmless to the environment.

The relationship between the input and output of each enterprise can be determined by the production function. The production function in this paper draws on the form of Cobb-Douglas production function and makes equations (1) and (2).

$$O_{i,1} = A \bullet I_{i,1}^{\alpha_{i,1}} \bullet I_{i,2}^{\alpha_{i,2}} \bullet \ldots \bullet I_{i,l}^{\alpha_{i,l}} \tag{1}$$

$$O_{i,2} = B \bullet I_{i,1}^{\beta_{i,1}} \bullet I_{i,2}^{\beta_{i,2}} \bullet \ldots \bullet I_{i,l}^{\beta_{i,l}} \tag{2}$$

Where, A and B represent the comprehensive technical level corresponding to economic output and waste output, respectively, in the production process, and $\alpha_{i,j}$ and $\beta_{i,j}$ are the elastic coefficients of various resources relative to the economic output and by-product output of the enterprise, respectively.

Environmental taxes are levied on waste released into the environment. The amount of tax is usually based on how harmful the waste is to the environment. In the context of environmental taxation, the total income of the enterprise is calculated by the economic income minus the environmental tax. Assume that the intensity of environmental taxation is r and the total income of enterprises is R_i, then we have equation (3).

$$R_i = O_{i,1} - r \bullet O_{i,2} \tag{3}$$

In addition, it is assumed that the enterprises in the industrial symbiosis network come from n different industries with symbiosis potential. Without loss of generality, it is assumed that the by-products produced by industry m can be invested as a production resource by enterprises in industry $m+1$.When enterprises establish the corresponding industrial symbiosis relations, the waste discharged into the environment by upstream enterprises will be reduced, and the corresponding environmental tax expenditure will be reduced.

3.2. Settings of node behaviour and connection rules

Each enterprise in the network can independently decide whether to cooperate with other nodes in the operation process. When enterprises cooperate with each other, corresponding connections will be formed between network nodes. We call the connection based on economic cooperation relationships as economic connections, and the connection based on industrial symbiosis relationships as industrial symbiosis connections. In the simulation process, each node has a limit on the maximum number of connections that it could initiate. This is because enterprises need to pay a certain amount of energy and cost to establish cooperative relationships. In network models in the field of social network analysis, when connections between nodes require a certain cost to build and maintain, the number of connections that can be established between nodes is usually limited. When Fraccascia et al. [23] studied redundancy in industrial symbiotic business development, in the simulation model built, the number of connections built between cooperative enterprises is no more than five. We use the same Settings in this research. We also refer to the setting of [22,23,33,39] to set the decision-making process of agents to build our model.

Specifically, for enterprise i and enterprise j, if the output elasticities of resource k follow $\alpha_{i,k} < \alpha_{j,k}$, indicating the efficiency of using this resource of enterprise j is higher than that of enterprise i, then enterprise i can benefit from establishing an economic connection with enterprise j. When both enterprises could benefit from such a relationship, and the initiator does not exceed the maximum number of connections, this economic connection could be established. And the production function of both parties is adjusted as equation (4).

$$O_{i,1} = O_{j,1} = A \bullet I_{i,1}^{\max\left(\alpha_{i,1},\alpha_{j,1}\right)} I_{i,2}^{\max\left(\alpha_{i,2},\alpha_{j,2}\right)} \ldots I_{i,l}^{\max\left(\alpha_{i,l},\alpha_{j,l}\right)} \tag{4}$$

When the by-product of one enterprise could be used as another's input resource, establishing an industrial symbiosis connection will reduce the by-product discharged into the environment and reduce the environmental tax of this enterprise at the same time. When the emission $O_{i,2}$ of enterprise *i* is less than the demand $I_{j,l}$ of enterprise j for this by-produce, the emission of enterprise *i* will be completely absorbed, where the amount of the valorised by-products is $O_{i,2}$. Otherwise, if $O_{i,2}$ is larger than $I_{j,l}$, the emission of enterprise *i* will be partially absorbed, and the amount discharged into the environment is $O_{i,2} - I_{j,l}$, where the amount of the valorised by-products is $I_{j,l}$. When such industrial symbiosis exists between any two enterprises and the party initiating the connection does not exceed the limit of the maximum number of connections, the industrial symbiosis connection could be established.

Fig. 1 shows the flow chart of agent decision-making process. Such a process is repeated until the network is finally fixed.

3.3. Running steps of the simulation program

First, the specified number of nodes is generated, and the variable values are initialized.

Then, we do the following for each node: 1) Check the possible benefits of this node when cooperating with any other nodes and form a sorted sequence of the partners of this node according to the benefits. 2) When the number of existing connections of this node is less than the maximum number of connections, and the first node in the sequence that can also benefit from mutual connections, this connection is established. 3) If there is industrial symbiotic cooperation between these two nodes, mark this connection as an industrial symbiotic connection. Otherwise, mark it as an economic connection. The networking process stops until all nodes have reached the maximum number of connections, or there are no more nodes to find partners.

Finally, the total economic output and waste emissions of the network are calculated. The economic output of the network is the sum of the economic outputs of all nodes, namely $O_1 = \sum O_{i,1}$. And the waste emissions of all nodes add up to the total waste emission of the network, denoted by $O_2 = \sum O_{i,2}$.

The effect of environmental taxation on network structure and performance can be observed by running the above model under different tax intensities. First, we explore the impact of environmental taxation on the structure of industrial symbiosis networks. The industrial symbiosis networks formed under different environmental tax rates have overall morphological characteristics, and some important network structural characteristics of them are calculated, such as the number of different kinds of connections, network connectivity, clustering, and small-world coefficient. Then we examine the impact of environmental taxation on the performance of industrial symbiosis networks. The performance indicators we consider here includes the economic performance and the ecological performance of the network, including aggregate and individual economic gains, as well as the utilization and emission of by-products. In addition, in order to more clearly reflect the impact of environmental taxation intensity, we also focus on the analysis and comparison of three scenarios, in which environmental taxes are low, medium and high respectively.

4. Simulation results

The purpose of this model is to study the impact of environmental tax on industrial symbiotic network, so we let the intensity of environmental taxation r $\in [0,1]$. Besides, we also need to set a series of other parameters to initialize the model, such as the size of the

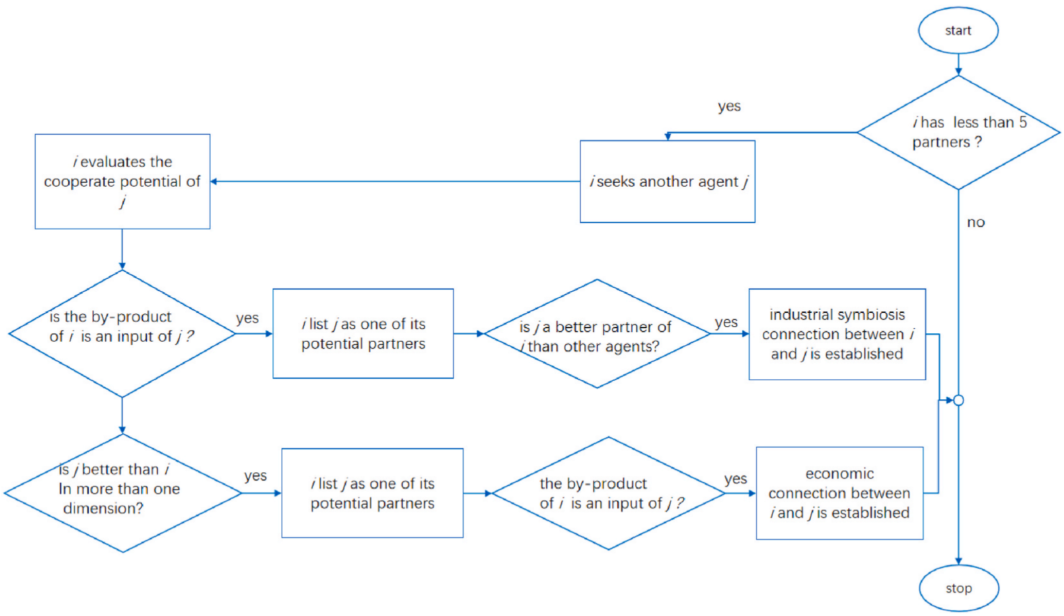

Fig. 1. The flow chart of agent decision-making process.

network, the number of input resources dimensions, number of enterprise types and the comprehensive technology levels. We use the method of literature [20] to set such parameters, which further uses the actual values of two real industrial symbiosis networks [21,40] to calibrate the initial settings of model parameters. We also conduct a robust test to show that the variation of these parameter values in the range near initial values will not change the research conclusion of this paper.

On this basis, we let the network size $N = 100$, the number of dimensions of input resources in the input-output vector $l = 3$, the number of enterprise types $m = 4$, the comprehensive technology levels $A = 4$ and $B = 1$. The maximum number of connections initiated by each node is 5. In each dimension of the input-output vector, the amount of input resource $I_{i,k}$ is generated by a random variable uniformly distributed from 0 to 10, and elastic coefficients $\alpha_{i,k}$ and $\beta_{i,k}$ are both generated by random variables uniformly distributed from 0 to 1. The simulation software NetLogo [34] is used to write the program and run the model under different intensities of environmental taxation, so that the corresponding structure and performance of industrial symbiosis network can be obtained. By repeating the model for 1000 times, results with significant statistical differences can be obtained under different parameter values.

4.1. Impact of environmental tax on industrial symbiosis network structure

Firstly, we investigate three different scenarios of low ($r = 0$), medium ($r = 0.5$), and high ($r = 1$) intensity of environmental taxation. Fig. 2 shows the resulting industrial symbiosis network of the model.

As can be seen from Fig. 2 (a), when the intensity of environmental taxation is 0, that is, when the government does not levy the environmental tax, there are many economic connections in the industrial symbiosis network, and the structure has obvious characteristics of random network. As can be seen from Fig. 2 (b), with the increase in the intensity of environmental taxation, the number of economic connections in the network decreases, while the number of industrial symbiosis connections increases, the randomness of network structure gradually decreases, and the circular structure among different types of enterprises gradually increases. As can be seen from Fig. 2 (c),

When the intensity of environmental taxation is exceedingly high, the connections in the network are mainly industrial symbiotic connections, and the network structure becomes an obvious circular structure. The total number of network links, the number of economic connections, the number of industrial symbiosis connections, as well as the mean and standard deviation of some important network structure indicators such as the average path length, the clustering coefficient and the small-world coefficient are shown in Table 1. The values of indices are reported as mean values followed by standard deviations (the values in the parentheses). The three scenarios were significantly different at the significance level of 0.001.

The number of connections in different types varies with the intensity of environmental taxation are shown in Fig. 3.

As can be seen from Fig. 3, the number of economic connections decreases with the increase in the intensity of environmental taxation, while the number of industrial symbiosis connections increases with the increase in the intensity of environmental taxation. In the case that the government does not levy an environmental tax, to maximize their own interests, enterprises will not suffer any loss in their emission of by-products. Therefore, enterprises are less motivated to form industrial symbiosis connections and tend to form more economic connections to improve their income. The collection of environmental tax will internalize the cost of by-product emissions of enterprises. To reduce the tax burden, enterprises must take measures to reduce emissions, thus making enterprises tend to form more industrial symbiosis connections. The pressure brought by environmental tax can encourage enterprises to exploit the potential of external connections as much as possible and carry out more cooperation, thus bringing about the growth of the total number of connections. The above mechanism causes the structural characteristics of the industrial symbiotic network to change with the change of the intensity of environmental taxation.

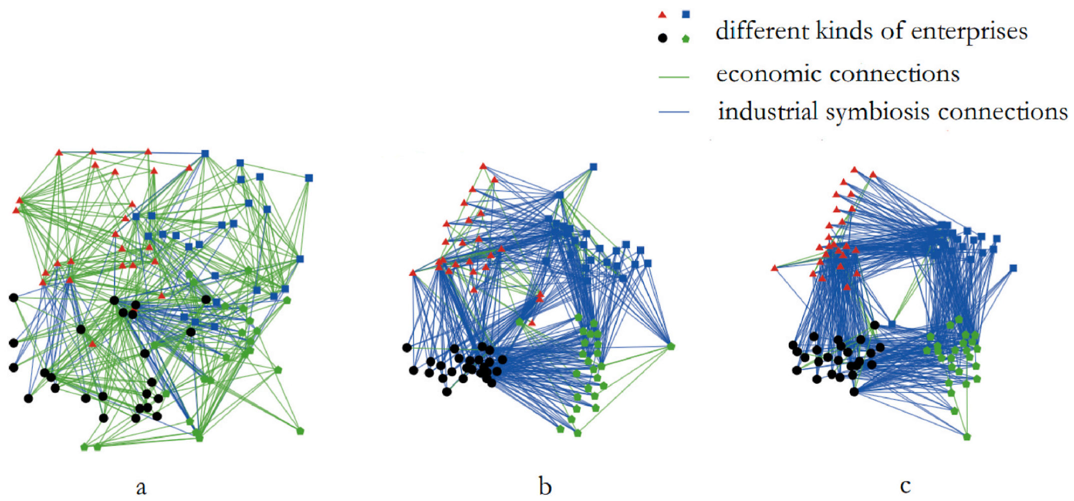

Fig. 2. The industrial symbiosis networks of three different scenarios. (a) $r = 0$. (b) $r = 0.5$. (c) $r = 1$.

Table 1
Network structure index in different scenarios.

Network structure indices	Scenario I	Scenario II	Scenario III
Number of links	460.660 (4.863)	498.860 (1.337)	499.841 (0.443)
Number of economic connections	348.169 (13.098)	59.10 (13.22)	22.07 (7.41)
Number of industrial symbiosis connections	112.491 (12.662)	439.76 (13.51)	477.77 (7.53)
Average path length	2.356 (0.070)	2.32 (0.035)	2.398 (0.032)
Clustering coefficient	0.335 (0.059)	0.102 (0.034)	0.038 (0.021)
Small world coefficient	0.142 (0.026)	0.044 (0.015)	0.016 (0.009)

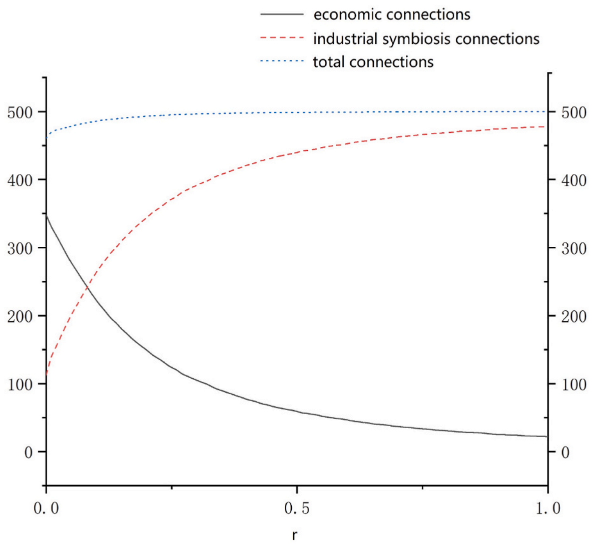

Fig. 3. The number of connections in different types varies with the intensity of environmental taxation.

Fig. 4 shows the variation of network average path length, aggregation coefficient, and small-world coefficient with the intensity of environmental taxation.

As can be seen from Fig. 4, although the impact of environmental taxation on the average path length of the network shows an inverted U-shaped change, the changing volume is small. Therefore, the accessibility between any two points of the network and the mediation effect of the intermediary nodes do not have a significant impact on the network function under this topology. However, the clustering coefficient of the network decreases rapidly with the increase of the intensity of environmental taxation. As a result, the

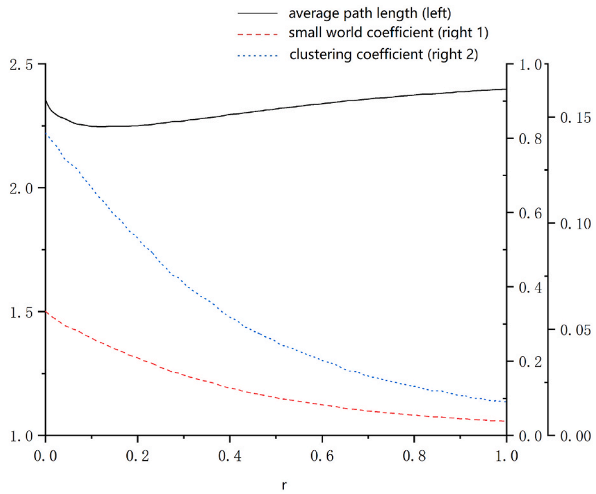

Fig. 4. The variation of network average path length, aggregation coefficient, and small-world coefficient with the intensity of environmental taxation.

small-world coefficient also decreases with the increase in the intensity of environmental taxation and remains smaller than the emergence level of small-world networks [34]. It indicates that industrial symbiosis cooperation is difficult to produce aggregation effect in the network topology, so it rarely produces geographic aggregation in real practice. To bring the aggregation effect to industrial symbiosis systems, it becomes important for the government to intervene in the early period of constructing industrial symbiosis networks. Many successful practices in which the government plans ecological parks through administrative means to construct industrial symbiosis networks also in turn confirm this conclusion [17,18,26].

4.2. Impact of environmental taxation on the performance of industrial symbiosis networks

We investigate the performance of industrial symbiosis networks from 3 aspects of economic output, by-product discharge, and by-product valorisation. Efficient industrial symbiosis networks are those that can simultaneously produce high economic revenue, minimize waste emissions, and make use of more by-products. The influence of environmental taxation on the establishment of different types of network connections among enterprises in the industrial symbiosis network not only causes the change of network topology, but also changes the internal mechanism of network performance. Table 2 shows the network outputs of the three different scenarios. Economic output is aggregated by the production function of all the agents, and it could also be added up by income of agents and the total amount of tax levied. By-products discharged is the aggregated discharged (not been reused) by products of all the agents. By-product valorised is the aggregated reused by-product under the action of all of the industrial symbiosis connections. Tax collected is the tax levied under certain taxation intensity. And enterprise average earning is the output minus the tax of all the agents. The indicators of the three scenarios were significantly different at the significance level of 0.001.

Fig. 5 shows how the network performance varies with the intensity of environmental taxation.

As can be seen from Fig. 5, with the increase in the intensity of environmental taxation, both economic output and by-product emissions are decreasing, while valorised by-product is increasing. This result reflects the contradiction between economic development and environmental protection. If the intensity of environmental taxation is too low, although it will speed up the economic development, it will cause too much damage to environment. On the contrary, if the intensity of environmental taxation is too high, although it can protect the environment, it will bring adverse effects on economic development.

Furthermore, Fig. 6 shows the variation of the average revenue and average emissions of enterprises with the intensity of environmental tax. Compared with Fig. 6, the by-product emissions of a single enterprise and the total emissions have a similar trend. However, the average income of individual enterprises is falling faster than the total network output. It includes not only the reduction of economic output caused by the adjustment of environmental tax to the cooperation strategy between enterprises (i.e., the choice of different types of connections), but also the direct erosion of taxation on the profits of enterprises. Therefore, in a sense, the impact of environmental taxation on the profitability of individual enterprises is greater than the impact on the whole economy. Therefore, how the government should use the increased tax revenue to support the enterprises in this process is an important topic, but it is beyond the scope of this research.

In conclusion, the government can effectively intervene in the formation process of the industrial symbiosis network by adopting the method of environmental taxation, and the intensity of environmental taxation will have a significant regulating effect on the structure and performance of the industrial symbiosis network. At the same time, the government is also required to be careful in formulating environmental tax policies, because the government needs to find a balance between economic development and environmental protection. In the face of the contradiction between the two, we suggest the government can take the following measures. Firstly, determine an acceptable minimum economic growth rate according to the actual needs of economic development, to induce a lower limit of the intensity of environmental taxation. Then an acceptable maximum pollutant discharge is determined according to the carrying capacity of the environment, and an upper limit of environmental tax intensity is obtained. Then the appropriate environmental tax collection policy should be formulated within this acceptable range, and the policy should be adjusted carefully according to the changes of economic development and ecological condition of the environment in the process of implementation. If the lower limit is higher than the upper limit for an industry, it indicates that the current contradiction between economic output and environmental protection in the industry can no longer meet the requirement of development, so it must implement transformation or elimination as soon as possible.

5. Robustness tests

The robustness of the results is discussed in two aspects: 1) other values of model parameters; 2) other forms of random variables in

Table 2
Network performance of different scenarios.

Network performance	Scenario I	Scenario II	Scenario III
Economic output	114,516 (17,611)	94,083 (16,288)	87,493 (14,522)
By-product discharged	10,386 (1010)	7162 (851)	6832 (785)
By-product valorised	321 (47)	1379 (100)	1476 (98)
Tax collected	0 0	89,532 (10,634)	170,800 (19,629)
Enterprise average earning	1145 (176)	45 (172)	−833 (220)

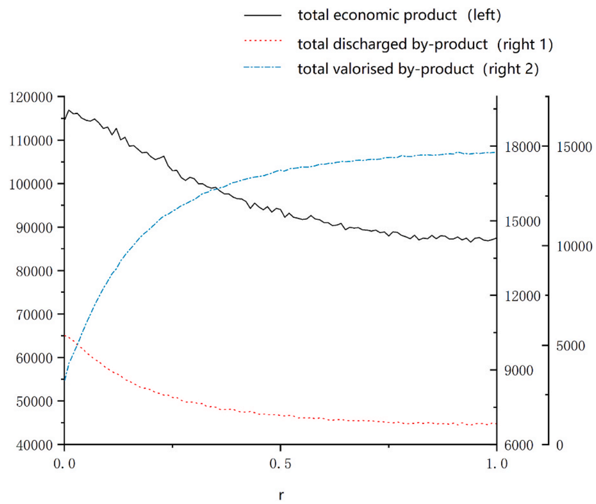

Fig. 5. The variation of network performance with the intensity of environmental taxation.

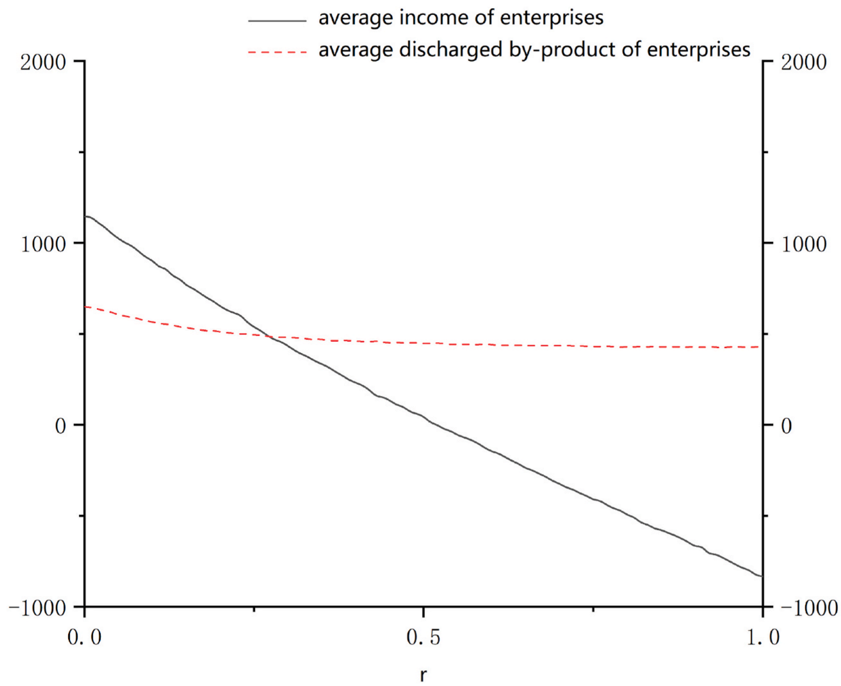

Fig. 6. The variation of average revenue and average emissions of enterprises with the intensity of environmental taxation.

the production function.

First, the values of the exogenous variables involved in the model were adjusted, respectively, and the model was rerun when the values of other variables remained unchanged. For network size N, the cases of $N = 80, 160, 240$ are tested. For the dimension of input-output vector, the cases of $l = 2, 4, 5$ are respectively run. For the number of enterprise types, the cases of $m = 3, 5, 6$ are tested, respectively. The maximum number of connections is tested respectively when $M = 4,6,7$.The case of $\mathrm{A} = 2, 6, 8$ is tested with $\mathrm{B} = 1$ fixed. These experimental results also show that the conclusions in this paper are robust at least when the parameter values of the basic model vary at a moderate level.

Second, in the production function, the economic and by-product output $O_{i,1}$ and $O_{i,2}$ are calculated by the amount of each kind of resource $I_{i,k}$ and the elastic coefficients $\alpha_{i,k}$ and $\beta_{i,k}$. In the basic model, these parameters are generated by random variables with uniform distribution. We also tried normal distribution and some standardized operation process. All these changes lead to the same conclusion, which shows the robustness of the conclusion in this research.

6. Discussions and conclusions

6.1. Discussions

Constructing industrial symbiosis networks is a basic institutional arrangement for enterprises to cope with the challenge of greening. It is of great significance to change the economic growth model and realize the “win-win” development of economy and environment. This paper establishes a simulation model of the formation process of industrial symbiosis networks using the agent-based modelling method. The relationships between enterprises in the network are defined by the dimensions of economic connections and industrial symbiosis connections. And the impact of environmental taxation on the structure and performance of industrial symbiosis networks is further explored on this basis. The main findings of this research are as follows.

First, with different intensities of environmental taxation, the industrial symbiosis network will form different structures. Enterprise in industrial symbiosis networks not only have the economic characteristics of pursuing benefit maximization, but also have the ecological characteristics of consuming the by-products of other enterprises such as “food” [4,5]. This determines the complexity of relations between members of industrial symbiosis networks and leads to a complex structure of two kinds of relationships of economic connections and industrial symbiosis connections [6,7]. Because environmental taxation can internalize the external costs of discharging by-products by enterprises, it can regulate the behaviour of enterprises and the relations between them, and thus exert an important influence on the structure of the industrial symbiosis network [13,16]. On this basis, this research further explores the impact of environmental tax intensity on the structure of industrial symbiotic network. When there is no environmental tax (that is, the intensity of environmental taxation is 0 in the model), the cooperative relationships between enterprises are mainly economic connections, the industrial symbiosis connections are few, and the generated network structure has the structural characteristics of random networks. With the increase of the intensity of environmental taxation, the economic connections within the network are gradually replaced by increasingly industrial symbiosis connections, which makes the structure of the industrial symbiosis network gradually change from a random network to a circular structure. When the intensity of environmental taxation is exceedingly high, the cooperative relationships between enterprises are mainly industrial symbiosis connections, the economic connections are very few, and the generated industrial symbiosis network has a rather regular circular structure.

Second, different industrial symbiosis network structures will lead to different network performance. By establishing economic connections among enterprises in the industrial symbiosis network, they can benefit from each other in the utilization ability of economic resources to achieve the purpose of win-win cooperation [31], thus greatly improving the economic output of both parties and the economic performance of the whole network [32]. At the same time, through the establishment of industrial symbiosis connections between enterprises, the wastes of some enterprises can be put into production as the resources of other enterprises [25, 26], thus reducing waste emissions and environmental pollution, and thus improving the ecological performance of the whole network [22]. However, due to the limited capabilities and resources of enterprises [23], the cooperative relationships that enterprises can initiate are limited, and the increase of ecological connections will inevitably reduce the number of economic connections in the network, thus reducing the economic output of the whole network. On this basis, this study further explores the relationship between the structural characteristics of industrial symbiotic network and network performance under different environmental tax intensities. When the network structure is a random network, the connections in the industrial symbiotic network are dominated by economic connections, the whole network has higher economic output and higher by-product discharge. When the network structure changes from random network to a circular network, the by-product emission and economic output of the industrial symbiosis network both decrease. When the network structure is circular, the economic output and by-product both stay at a rather low level. We also find that the depressing effects of network structure on the income of individual enterprises are much more severe than that on the total economic product.

6.2. Conclusions

At present, studies on the construction of industrial symbiosis networks are still in the initial stage. Because the industrial symbiosis network itself is difficult to measure, scholars mainly use the case methods to analyse the specific approaches of the construction of an industrial symbiosis network in a specific region. There are still insufficient research results to analyse the formation mechanism of industrial symbiosis networks and study the influence of government policies on the structure and performance of industrial symbiosis networks systematically and comprehensively. The results of this study provide new ideas for the study of industrial symbiosis networks and theoretical guidance for the government to adjust the structure and performance of the industrial symbiosis networks through environmental tax policy.

First of all, our research on industrial symbiosis has certain methodological advantages. Many studies have used empirical and case methods to study industrial symbiosis system [21]. However, this kind of research focuses more on the status and performance of industrial symbiosis system, among which case study is more suitable for the “clean-slate” theories, while empirical study is more suitable for the extensively developed theories. However, the advantage of our simulation approach is that it can greatly enhance the accuracy of the theory, the relevant internal validity, and the interpretation and exploration of the theory through computer experiments. This is because computer simulation of phenomena and experiments can greatly deepen the understanding of basic theories [41].

Secondly, this study contributes a new perspective to the multi-agent simulation of industrial symbiosis systems. At present, some scholars have explored the research paradigm of using multi-agent simulation method to study industrial symbiosis system [23], and adopted multi-agent simulation method to explore the role of some important factors affecting industrial symbiosis system behaviour and function. For example, Fraccasia and Yazan [22] discussed the impact of online information sharing on IS performance. Fraccasia et al. [33] discussed the role of redundancy in IS business development. This study discusses the impact of environmental taxation on the structure and performance of industrial symbiosis system. We confirm the view of existing literatures that environmental taxes can have a significant impact on industrial symbiotic networks, and further indicate how environmental taxes affect the structure of industrial symbiosis networks. This study also establishes the links between environmental tax, industrial symbiosis network structure and the output of industrial ecological networks, and the impact of environmental taxation on the economic and environmental efficiency of industrial ecological network is further presented.

Based on these theoretical contributions, some feasible suggestions for the government to adopt environmental taxation to adjust the structure and performance of industrial symbiosis networks are put forward. The model results indicate that environmental taxation is an important means for the government to balance the contradiction between industrial development and ecological environment. Yet the government needs to be careful in determining the intensity of environmental taxation. If the intensity is too low, it will not be enough to help protecting the environment. On the other hand, if the intensity is too high, it will bring unnecessary damage to economic development. This paper suggests a practical path for the government to determine the intensity of environmental taxation. First, according to the acceptable minimum economic development goal to establish the lower limit of the intensity. And then establish an upper limit of intensity according to the objectives of environmental protection. The appropriate intensity of environmental taxation should be set between the two limits and be adjusted with the change of economic and environmental protection goals. For some industries, if the lower limit is higher than the upper limit, it indicates that the current contradiction between economic development and environmental protection in the industry can no longer meet the requirement of development. Such industries need transformation or elimination in this situation.

Data availability

Data included in article.

Ethics statement

Review and/or approval by an ethics committee was not needed for this study because no laboratory experiments were conducted with the students (respondents) and no human experimental data was used for analysis in this study.

Informed consent was not required for this study because no laboratory experiments were conducted with the students (respondents) and no human experimental data was used for analysis in this study.

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CRediT authorship contribution statement

Lei Hua: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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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