Journal of Cleaner Production 450 (2024) 141689

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Exploring coevolution in the diffusion of green products between consumers and enterprises—An agent-based model of two-layer heterogeneous networks

Zhongjie Zhang, Zhangang Han *

School of Systems Science, Beijing Normal University, Beijing, 100875, China

A R T I C L E I N F O

Handling Editor: Tomas B. Ramos

Keywords:
Green products
Green consumption
Diffusion
Complex networks
Agent-based modelling

A B S T R A C T

China has implemented comprehensive low-carbon policies to promote the widespread adoption of environmentally friendly technologies. However, the complexity of interdependent consumer and enterprise decisions poses challenges to this process. In this study, we propose a new approach that combines complex networks and agent-based modelling (ABM) to develop a framework for the collaborative evolution of consumer and enterprise responses to green product promotion. We also innovatively include social factors in our model. This study investigates the impact of various factors on the adoption of green products, including consumer subsidies, government education and propaganda and carbon pricing. The results show that consumers and enterprises exhibit similar strategic evolutionary trends due to their interdependence and mutual influence. Consumer subsidies can effectively stimulate the widespread adoption of green products. Government education and propaganda activities in the initial stages of promotion can effectively drive the proliferation of green products at a relatively low cost. Carbon pricing plays a dual role in promoting the proliferation of green products. Lower carbon pricing has a minimal influence on the overall equilibrium proportions between traditional enterprises and green product enterprises. Higher carbon pricing can act as a catalyst for enterprise-level transformation, encouraging businesses to transition towards greener practices. Sensitivity analysis reveals that consumer subsidies remain the most critical factor in promoting green products, even in the presence of social factors. Demand-side policies can more effectively facilitate the promotion of green products.

1. Introduction

With rapid economic development, resource and environmental problems have become increasingly prominent, affecting the high-quality development of the social economy (Hojnik et al., 2021). Many countries have adopted policies to promote green transitions. The global challenges posed by environmental degradation and resource depletion have underscored the pivotal role of green technologies. However, the widespread adoption of these technologies faces formidable hurdles. A significant impediment to their dissemination lies in the nascent stage of high-cost innovations (Bratanova et al., 2016; Xu et al., 2017). Extensive research and the implementation of various fiscal measures, such as taxes and subsidies, have been diligently pursued to catalyse the diffusion of green technologies (Bratanova et al., 2016; Bi et al., 2017; Zhang et al., 2019), with the expectation that heightened technological maturity will ultimately lower costs. Nonetheless, to propel consumers' engagement with green technologies, relying solely on technological advancement falls short (Axsen and Kurani, 2012). The impact of social interactions on consumer adoption of innovations is equally important. (Axsen and Kurani, 2012; Arvanitis and Ley, 2013). The diffusion of green technologies is not confined to a mere commercial endeavour but encompasses the evolution of societal consensus. Various nations have dedicated substantial resources to bolster the public's environmental awareness (Gifford and Nilsson, 2014), exerting a profound influence on collective attitudes and consequently reshaping the adoption patterns of green technologies. Empirical evidence has consistently affirmed that consumers with heightened environmental consciousness are more disposed to embrace green technologies (Suki et al., 2016; Degirmenci and Breitner, 2017; Prayoga et al., 2020). As environmentally conscious attitudes become ingrained within society, it becomes imperative to account for the fluid interactions and evolving attitudes among consumers when analysing the diffusion of green

* Corresponding author.
E-mail address: zhan@bnu.edu.cn (Z. Han).

https://doi.org/10.1016/j.jclepro.2024.141689
Received 14 September 2023; Received in revised form 26 February 2024; Accepted 5 March 2024
Available online 6 March 2024

technologies.

Previous studies have focused on the impact of supply-side regulatory policies on the diffusion of green products (Li and Gao, 2022; Noll et al., 2014; Shi et al., 2021; Zheng et al., 2022), ignoring the important impact on the demand side. In addition to consumers' demand for green products, a well-explored factor that fosters the diffusion of green products and practices is conformity to trends (Young, 2011). Innovations such as electric vehicle control naturally involve uncertainty triggered by insufficient knowledge. In such situations of uncertainty, the opinions and behaviours of friends and neighbours often serve as a guideline for individuals' own behaviours (Cialdini and Goldstein, 2004; Nolan et al., 2008; García-Maroto et al., 2015). Moreover, in empirical research, peer effects have been found to increase the adoption of solar panels (Bollinger and Gillingham, 2012) or reduce residential energy usage (Ayres et al., 2011; Frederiks et al., 2015; Schultz et al., 2018).

The aim of this study is to provide a more systematic perspective for the promotion of green products, considering various factors such as supply, demand and peer influence and so on. To achieve this, we propose a new joint regulatory framework that takes into account both the supply and demand sides and develop a novel agent-based model of green product diffusion. In addition to considering economic influence, we introduce social influence as another factor of decision behaviour. Using the information interaction mechanism and a behavioural decision-making model of manufacturer and consumers embedded in different social networks, we explore the diffusion process and emergence mechanism of green products under different regulatory policies on both the supply and demand sides.

The rest of this paper is organized as follows. Section 2 reviews the related literature. Section 3 outlines the methodology and model construction procedure. Section 4 presents the simulation results. To better compare the results with those of other existing studies, a discussion is presented in Section 5. Section 6 summarizes the study's conclusions and highlights its policy implications.

2. Literature review

2.1. Green product diffusion

Green products not only satisfy users' functional needs but also economically reduce energy and resource consumption throughout their lifecycle while mitigating or eliminating environmental pollution, thereby yielding positive ecological effects (Li et al., 2018). Scholars have conducted research on the dissemination of green products to aid in their absorption in the market. The most typical model is the Bass model (Bass, 1969, 2004; Mahajan et al., 1990, 1995), which is defined by a simple differential equation that characterizes diffusion as a contagious process initiated by mass media and propelled by word of mouth. In the realm of green innovation, variants of the Bass model have been applied to study the diffusion of wind power technology (Usha Rao and Kishore, 2009), green electricity prices (Diaz-Rainey and Tzavara, 2012), stationary fuel cells (Heinz et al., 2013), household energy efficiency technologies (Diaz-Rainey and Ashton, 2015), photovoltaic system support programmes (Islam, 2014; Radomes and Arango, 2015), and consumer demand for smart metering electricity prices (Rixen and Weigand, 2013). However, comprehensive innovation diffusion models such as the Bass model have limitations in terms of their predictive ability and explanatory power. They are not designed for analysing hypothetical scenarios, lack an explicit consideration of consumer heterogeneity, and overlook the complex dynamics and interpersonal relationships in real-world social systems.

The diffusion of technology and innovation is inherently a dynamic process. However, a substantial body of literature on low-carbon diffusion has not emphasized its dynamic aspects. This situation is not surprising because traditional methods such as differential equations and system dynamics lack the capacity to explore dynamic systems by integrating the microlevel activities of each individual with the macrolevel behaviour of the system. Integrating of these two perspectives is crucial because low-carbon diffusion systems are not designed in a predetermined manner; rather, they emerge through self-organization through frequent interactions among individuals. In essence, such systems are complex adaptive systems. A powerful tool for bridging the gap between micro- and macrolevel systems is agent-based modelling (ABM). ABM provides the necessary flexibility; thus, ABM methods have been widely used to explore, predict, and assess innovative products and technologies. Zhang et al. (2011) employed ABM to explore the factors accelerating the diffusion of alternative fuel vehicles. Rai and Robinson (2013) used ABM to study the determinants of the spatiotemporal patterns in the adoption of solar photovoltaics in the residential sector. Silvia and Krause (2016) utilized ABM to assess the impact of government policies on the purchase of electric vehicles. Zeng et al. (2020) simulated the competitive dynamics between renewable energy technologies and traditional energy technologies using ABM, considering factors such as the market entry sequence, prices, changes in preferences, and technological improvement rates. Leveraging ABM to address the shortcomings of traditional diffusion models holds great promise. By integrating ABM, traditional empirical frameworks can embed agent states, decision rules, and environmental variables. Researchers can use a bottom-up perspective to solve problems. Therefore, using an Agent-Based Model in the context of product diffusion allows for a focus on individual behaviour during the diffusion process, effectively addressing the neglect of individual heterogeneity and environmental variables in the Bass model.

2.2. Peer effects and green product diffusion

In complex and dynamic economic environments, relying solely on individual or organizational information for decision-making is no longer sufficient to meet diverse needs. Peer businesses, especially that share key characteristics within the same industry, provide valuable insights, as they often face similar decision-making challenges and are worth emulating. Enterprises tend to engage in social learning and imitate their peers (Kelchtermans et al., 2020). Peer businesses play a significant role in determining a company's capital structure and investment decisions. Additionally, smaller and less successful enterprises are highly sensitive to larger, more successful peers (Leary and Roberts, 2010).

At the consumer level, when purchasing heterogeneous products, in addition to considering product prices, individuals often rely on the opinions and behaviours of friends and neighbours, in addition to considering product prices, who serve as a guide for their own behaviour. García-Maroto et al. (2015) explored the diffusion of residential solar photovoltaic systems in Connecticut and identified that interactions among residents played an important role in diffusion. Natalini and Bravo (2013) took into account the impact of neighbours' choices and developed an agent-based model to simulate the selection of means of transport among Americans. Regarding peer effects on innovation diffusion, companies within the same industry face similar market environments and development prospects.

Businesses need to not only compete for market share but also collectively elevate the legal status of green innovation to mitigate market risks. This dual relationship of competition and cooperation among peers generates frequent and intense interactions in green innovation, triggering imitative behaviour among enterprises. Therefore, green innovation behaviour may be influenced by industry peers, necessitating the inclusion of peer effects in the analytical framework of green innovation factors. Wang et al. (2022) analysed empirical data from 782 enterprises in China, providing evidence that the green innovation of enterprises is positively influenced by their peers. Huang et al. (2023) showed that peer effects on the environmental, social, and governance (ESG) practices of Chinese companies contribute to the creation of corporate value. Xiong et al. (2016) proposed a theoretical framework for peer effects on enterprise innovation diffusion, indicating that peer effects may occur through different types of relationships in complex networks, playing various roles in the diffusion process.

Existing studies have summarized the information exchange between individuals in the diffusion process as learning behaviours focusing solely on income disparities, such as the Experience-Weighted Attraction (EWA) learning mechanism (Wu et al., 2017; Chen et al., 2021) and Fermi learning rules (Zhang et al., 2019; Li et al., 2021). However, in the process of product diffusion, several noneconomic factors, such as product reputation, and consumer attitudes, have not been adequately addressed.

2.3. Government regulation and its role in green product diffusion

Government regulation is an effective tool for promoting the use of green products and plays a crucial role in achieving low-carbon economic strategic goals. We analyse government policies from both the supply and demand sides. On the supply side, taxation and subsidies are two major regulatory instruments for promoting the development of green industries. According to Yuyin and Jinxi (2018), government subsidies for energy-saving products can stimulate a reduction in carbon emissions and energy consumption. Tian et al. (2020) focused on the negative economic consequences of government regulation, as it does not necessarily improve manufacturers' environmental economic efficiency. Based on the game between the government and manufacturers in a complex network, Wu et al. (2017) established a low-carbon strategic evolutionary model and found that manufacturers' expectations of government subsidies, regulations, and other incentive measures determine whether the low-carbon strategy spreads and how quickly it spreads. Zhang et al. (2019) simulated the impact of the carbon trading market on the spread of green technologies among manufacturing enterprises in a Barabási–Albert (BA) scale-free network. In the process of green product diffusion, government, manufacturers, and consumers influence each other, and multiple stakeholders collectively impact the development of green industries (Li et al., 2019). Government incentive measures and consumer lifestyles have a significant impact on the sustainability of businesses (Alfarano et al., 2005).

On the demand side, the influence of green product diffusion is increasingly being emphasized. On the one hand, governments widely use green consumption vouchers to promote environmentally friendly consumption patterns. Li et al. (2019) found that consumer purchase subsidies can respectively promote new energy vehicle diffusion. Yang et al. (2022) also discovered that green subsidies can effectively enhance the diffusion of green products, they are unable to achieve full-scale adoption of such products. On the other hand, consumer awareness and emotions are also critical to promoting green products. For instance, Varela-Candamio et al. (2018) found that if the government actively educates and disseminates knowledge about green behaviour, it can motivate citizens to adopt green behaviour. Wang et al. (2018) empirically demonstrated that positive government education on green electric vehicles can successfully enhance people's purchase identity. Therefore, policies for the demand side are equally crucial.

2.4. Research gaps

In general, the literature exhibits the following gaps: (1) While some studies have discussed diffusion models of green products, they predominantly analyse them from a macrolevel perspective rather than from a microlevel subject perspective. The heterogeneous characteristics of businesses and consumers are often overlooked in traditional product diffusion models, and complex dynamics and interpersonal relationships in real-world social systems are not considered. Additionally, traditional models demonstrate limited predictive ability and explanatory power. (2) There is insufficient research on the complex interactions between businesses and consumers. In reality, business strategies are influenced by the attitudes and behaviours of their connected peers. When facing new products, consumers not only consider product prices but also rely on the opinions and behaviours of friends and neighbours, an often neglected phenomenon, known as the peer effect. (3) Simultaneous consideration of joint policy analysis from both the demand and supply sides is limited. Existing research focuses on specific groups, such as consumers or businesses, and it ignores the joint impact of policies across different groups.

To address these gaps, this paper integrates agent-based modelling and complex network theory to establish an agent-based model of heterogeneous networks. The aim is to explore new avenues for activating the diffusion of green products in China. This paper establishes a comprehensive analytical framework that simultaneously incorporates the demand and supply sides. Furthermore, it incorporates a decision-making model that combines economic influence and social impact in the market.

3. Methods

As mentioned above, ABM has unique advantages in research on behavioural decision-making at the microlevel of individuals. This study involves an agent-based model of two-layer heterogeneous networks, this model is used to simulate the diffusion of green products at different levels of enterprises and consumers. In this study, we choose new energy vehicles as a typical representative of green products. This choice involves various behaviours and decisions of agents (such as enterprise and consumer agents), including the purchase behaviour of new energy vehicles, the production behaviour of new energy vehicles, the evolution of social networks, and the evolution of individuals' attitudes towards new energy vehicles. Therefore, ABM will provide insights into the microscale diffusion path and further clarify the impact of new energy vehicle diffusion on the transformation of these consumers and enterprises. Next, we briefly examine ABM, including the framework and basic assumptions of the model.

3.1. Model framework

The structure of the model is shown in Fig. 1, which illustrates the main actors involved in the promotion of green products: the government, enterprises, and consumers. Government policy interventions influence the evolution of the system. Enterprise and consumer agents make decisions based on unique attributes. Given the complexity of the green product innovation system, intricate social networks provide an ideal simulation framework. Both enterprise and consumer agents are located in heterogeneous social networks at their respective levels.

At the consumer level, preferences for green and traditional products depend on economic utility and social impact. Social impact is positive if a consumer's friends have similar attitudes; otherwise, it is negative. Each consumer also has product preferences such as cost effectiveness and usage scenarios. These preferences are integrated, combining social impact and economic utility to form final product preferences.

At the enterprise level, enterprises operate in a competitive market and adopt different strategies to produce products. Enterprises connect through social networks, gaining insight into the revenues and strategies of neighbouring enterprises. By comparing products and profits, enterprises adjust their own production strategies.

In the interaction between these two levels, consumers, as users of green products, acquire products through the market. Conversely, enterprises, as producers of products, provide products to consumers based on market demand. Product demand is the basis for the co-development of the two dynamics. The strategies of consumers and enterprises are constantly adjusted under the influence of their respective dynamic social networks.

3.2. Basic assumptions of the model

Based on the outlined ABM and research questions, the assumptions of the collaborative evolutionary model of green products between

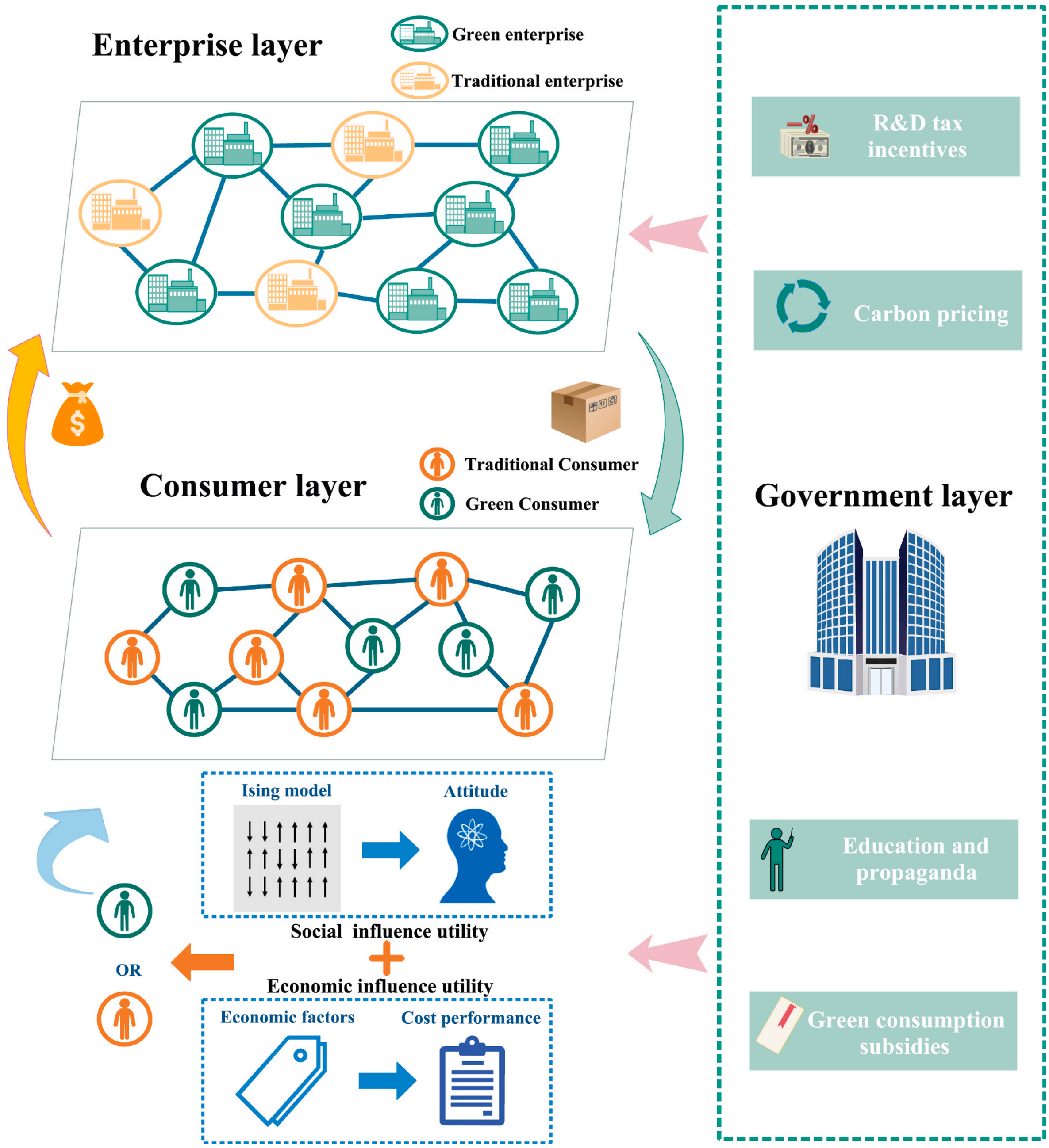

Fig. 1. Structure of the agent-based model of two-layer heterogeneous networks.

consumers and enterprises are as follows.

(1) The model includes two dynamic agents, consumers and enterprises, within two layers of heterogeneous social networks. These agents, bounded by rationality and faced with incomplete information, interact through repeated games or information exchange across layers to determine their optimal strategies. This process mirrors traditional evolutionary dynamics in group interactions (Schlag, 1998; Perc et al., 2013; Fan et al., 2022).

(2) The relationships between people are complex, and many social networks have been proven to exhibit small-world phenomena (Travers and Milgram, 1977; Kleinberg, 2000; Schnettler, 2009). Therefore, at the consumer level, we choose to use small-world networks to build social relationships, forming a social network with N_1 nodes and an average degree of d_1. Enterprises do not choose a fixed strategy; instead, they adjust their strategy based on the interests of their peers. Therefore, the network structure has certain rules to follow, but randomness also exists because many real networks support small-world network models (Fan et al., 2017; Li et al., 2017). For a network composed of enterprises, a given node represents an enterprise, and the edge between the nodes indicates that there is a direct relationship between the two corresponding enterprises. Then, the enterprises can form a network. As a kind of complex network, small-world networks have been widely applied to different problems of enterprises (Fan et al., 2017; Zhang et al., 2019; Shi et al., 2021; Chen et al., 2023a). Therefore, this study constructs a small-world network with N_2 nodes and an average degree of d_2 at the enterprise layer. Enterprises choose to produce green products or traditional products, and the proportion of enterprises producing green products is $E(t)$.

(3) Payoffs and strategies are shared only between connected nodes in the same network layer. Agents engage in repeated games with neighbouring agents, synchronously updating strategies. This updating rule is widely employed to simulate evolutionary dynamics in networks (Roca et al., 2009; Fan et al., 2022).
(4) Government influence occurs primarily through policies that affect consumers and enterprises, which are assumed to remain constant throughout the study period. Fluctuations in commodity prices are not considered, in line with previous evolutionary game theory research (Shi et al., 2020; Li and Gao, 2022; Chen et al., 2023b).
(5) This study assumes a perfectly competitive market where total demand is equally distributed among enterprises. Aggregate demand from green and traditional consumers is divided equally among enterprises producing corresponding products. Similar competitive market assumptions have been employed in previous studies within the field of energy economics and technology diffusion (Fan et al., 2022; Shi et al., 2021).

3.3. Model dynamics

3.3.1. Evolutionary dynamics model of the consumer layer

Building on the previously stated assumptions, we delve into the dynamics of the consumer layer. The decision-making process among consumer agents unfolds in two sequential stages: utility calculation and evolutionary learning. Initially, consumers assess the social impact and economic value of green products to decide between them and conventional options. In the evolutionary learning phase, individuals adjust their preferences based on their neighbours' attitudes towards green products. They integrate social influence and economic utility from neighbours, using social imitation and learning mechanisms to adjust their strategies. For visual clarity, Fig. 2 illustrates this process.

(1) Utility Calculation

The process of green consumer decision-making is dynamic, with information about green products, peer attitudes, and product value being gradually disseminated through social networks. As consumers internalize these data, their attitudes and strategies undergo changes. Consumer benefit hinges on two main factors: the influence of social relationships shaped by neighbouring consumers and the effect of product economic value on utility. Based on previous research (Laciana and Rovere, 2011; Weisbuch and Boudjema, 1999), we calculate consumer utility as shown in Eq. (1):

$$U_i^{ef} = \alpha U_i^{economic} + (1-\alpha) U_i^{social} \tag{1}$$

Here, U_i^{social} signifies consumers' attitudes influenced by neighbours, $U_i^{economic}$ represents economic utility based on product value, and α denotes the weighting coefficients of these factors.

First, we delve into the utility of social influence acquired by consumers under the impact of social networks within the framework of the Ising model. The "Ising model" of statistical physics was originally developed by Ernst Ising in 1925 to explain phase transitions in ferromagnetic materials. More recently it has been used to model several social processes, such as collective opinion formation (Galam, 1997; Pabjan, 2004; Grabowski and Kosiński, 2006) or the adoption of new technologies (Weisbuch and Boudjema, 1999). Building on the seminal work of Laciana and Rovere (2011), we use discrete variables to capture consumers' attitudes towards different product categories. A value of $+1$ indicates a positive inclination towards green products, while -1 reflects support for conventional alternatives. The level of social influence experienced by each consumer is determined by aggregating the states of neighbouring agents, denoted as $E_i^{neighbours}$ in Eq. (2). In the environment conducive to the adoption of green products, the choice of a purchasing strategy leads to favourable outcomes, while the choice of an opposite approach leads to negative impact, as illustrated in Eq. (3). This modelling highlights the complex interplay between public sentiment and strategic decision-making.

$$E_i^{neighbours} = \sum_{k=1(k\neq i)}^{N_F} \left(\frac{J_{ik}}{N_v^i}\right) S_i \tag{2}$$

The utility acquisition of social influence is denoted as U_i^{social}:

$$U_i^{social} = \begin{cases} \left|E_i^{neighbours}\right| & if\ V_i = +1, E_i^{neighbours} > 0 \\ -\left|E_i^{neighbours}\right| & if\ V_i = +1, E_i^{neighbours} < 0 \\ -\left|E_i^{neighbours}\right| & if\ V_i = -1, E_i^{neighbours} > 0 \\ \left|E_i^{neighbours}\right| & if\ V_i = -1, E_i^{neighbours} < 0 \end{cases} \tag{3}$$

Here, N_F represents the total number of individuals in the network, N_v^i denotes the number of individuals linked to the agent through the social network, J_{ik} signifies the social influence of neighbours on consumer agent decisions ($J_{ik} = 1$ if agents are adjacent, otherwise $J_{ik} = 0$), S_k is the opinion of agents towards green products ($S_i = 1$ and $S_i = -1$

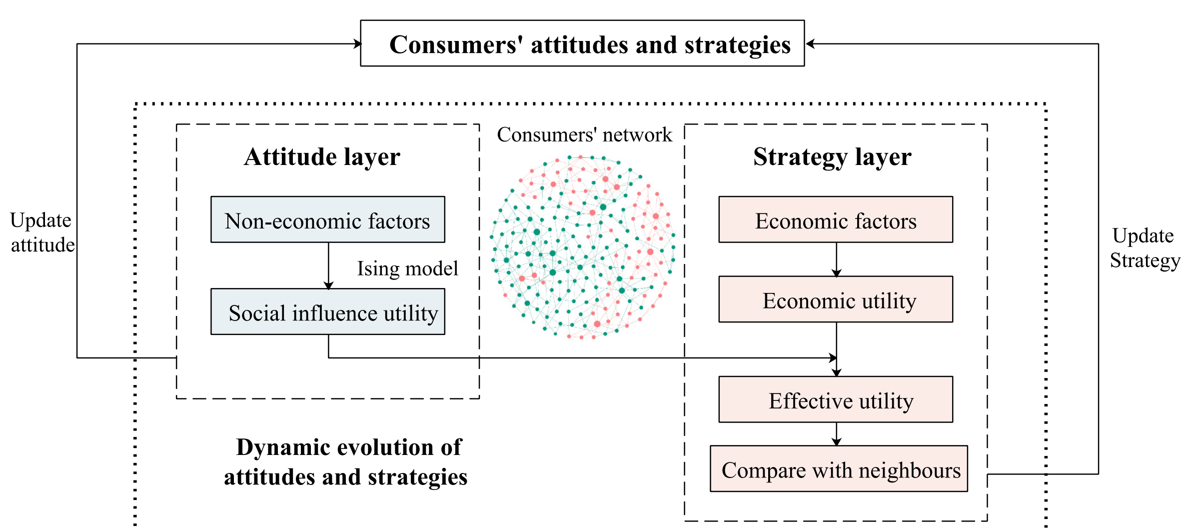

Fig. 2. Structural diagram of the evolution of attitudes and strategies evolution in the consumer layer.

signify positive and negative attitudes, respectively), and V_i represents the strategic choices made by consumers in product selection ($V_i = 1$ and $V_i = -1$ represent the strategies of purchasing green and traditional products, respectively).

Next, we study the effect of economic factors on consumer utility. Consumer i evaluates the affordability of purchasing a product at an economic price, either p_g or p_t. In this study, we choose the promotion of new energy vehicles as a case for studying the promotion of green products. To capture the heterogeneity of consumers, we assume that each consumer has a driving distance of D_i over the lifespan of the vehicle following a probability density distribution. As a result, factoring in economic aspects, the consumer's economic utility can be formulated as follows:

$$U_i^{economic} = \begin{cases} \frac{p_g}{D_i} - h_i \times (1 - E(t)) + S_r & V_i = +1 \\ \frac{p_t}{D_i} & V_i = -1 \end{cases} \tag{4}$$

where p_g represents the price of the green product, p_t represents the price of the traditional product, S_r represents the government subsidy for purchasing green products, and h_i reflects the expense incurred by consumers while seeking or using services for green products. In the context of the new energy vehicle industry, h_i can be interpreted as the availability of charging infrastructure, which is tied to the number of green product manufacturers. With an increase in the number of companies producing new energy vehicles, consumers can access more comprehensive support services.

(2) *Evolutionary Learning*

Consumer strategies within the social network demonstrate complex interplay where the collective outcomes of consumer choices are impacted by those of their neighbouring agents. Consumers possess two core attributes, attitudes and strategies, and our investigation focuses on exploring the interplay of these attributes.

Consumer attitudes towards green products are shaped by neighbouring agents' attitudes and external social factors. In the Ising model, a change in attitude change (equivalent to minimizing the free energy of the system) is achieved by spin flipping (Ising, 1925; Zheng et al., 2022). The system energy calculation is shown in Eq. (5) and Eq. (6).

$$E = -\sum_{i=1}^{N}\left(\sum_{k=1}^{N} w_{ik}s_k + B\right)S_i \tag{5}$$

$$dE = -2 * E \tag{6}$$

Here, E represents the total energy of the system; w_{ik} represents the coupling strength between neighbouring spins; $w_{ik} = 1$ indicates direct connectivity between spins i and k; otherwise, $w_{ik} = 0$. B denotes the external magnetic field, encompassing external interventions for green products such as public perception, media campaigns, and government initiatives.

This system tends to stabilize the lowest energy state, i.e., individuals' attitudes tend to become the same as their adjacent agents' attitudes. This phenomenon is similar to the reality that most people tend to be more aligned with the collective (Degroot, 1974; Dong et al., 2017; Xiong et al., 2017). If the energy change associated with a flip is negative, representing a decrease in free energy, the change is accepted. Conversely, if the energy change is positive, then probability of the state is determined by the Boltzmann distribution (Ising, 1925).

$$P^{social} = \exp(dE/\beta) \tag{7}$$

where β can be interpreted as the level of stochastic noise within the system.

Subsequently, at the succeeding time step, the spin state, which signifies the agent's attitude towards green products, undergoes an update:

$$S_i(t+1) = \begin{cases} -S_i(t) & with\ P^{social} \\ S_i(t) & with\ \left(1 - P^{social}\right) \end{cases} \tag{8}$$

By integrating Eq. (1) to ascertain the effective utility U_i^{ef} of consumers and considering their social networks, we utilize this framework to examine the evolution of consumer strategies. Consumer agent i randomly selects an agent from his or her social network to compare his or her effective utility U_j^{ef} and strategies. The probability of emulating the adjacent agent's strategy follows Eq. (9), a decision rule extensively employed in prior research (Perc et al., 2013; Hu et al., 2020; Shi et al., 2020; Chen et al., 2021; Zheng et al., 2022).

$$P_{i\to j} = \frac{1}{1 + \exp\left(\left(U_i^{ef} - U_j^{ef}\right)/k\right)} \tag{9}$$

In summary, consumers update their attitudes towards products based on the Ising model, incorporate their social networks, and revise their final product selection strategies by considering the economic value of the products.

3.3.2. *Evolutionary dynamics model of the enterprise layer*

Based on the model assumptions, we conduct an analysis of agents at the enterprise layer. This process is similar to consumer-layer decision-making in two phases: utility calculation and evolutionary learning.

(1) Utility Calculation

We employ the symbol j to denote the investment strategy of enterprise i at time t.

$$j = \begin{cases} 1 & green\ product \\ 2 & traditional\ product \end{cases}$$

In enterprise investment decisions, they consider the strategic choices of other enterprises. However, due to information constraints, enterprises cannot access all the details about others, leading to reliance on market conditions and their own anticipated returns. Thus, following Wu et al. (2017), we employ a multiagent adaptive expectation adjustment equation:

$$\theta_{ij}^{t} = (1 - \xi)\theta_{ij}^{t-1} + \xi b_{ij}^{t-1} \tag{10}$$

Here, θ_{ij}^{t} denotes the number of enterprises i expected to adopt strategy j at time t, while b_{ij}^{t-1} represents the actual number of enterprises i observed within their local neighbourhood implementing strategy j at time $t-1$. The adjustment factor ξ governs the extent of expectation adaptation, satisfying the condition $0 < \xi < 1$.

Within the enterprise network, enterprises can choose to produce green products or traditional products. If an enterprise chooses to produce green products, they will be successfully developed with probability φ (Chen et al., 2021). Unsuccessful research and development (R&D) attempts lead companies focus to exclusively on traditional product manufacturing. Similar methods have been used in green business transition studies (Chen et al., 2021; Fan et al., 2022). In this study, we designate the cost of green products as c_1 and the cost of traditional products as c_2. Innovation activities are characterized by diminishing returns to scale, indicating that the marginal returns from unit investment in R&D diminish. Enterprises typically model R&D costs using a quadratic function (Xiao and Xu, 2012; Iyer and Soberman, 2016; Chen et al., 2021). When investing in a specific R&D project, enterprises bear fixed costs that correspond to the fixed probability of success in R&D. Hence, the cost of R&D investment can be expressed as follows:

$$c(\varphi) = f\varphi^2 \tag{11}$$

where $f > 0$; clearly, this represents a sunk cost, meaning that enterprises incur costs even if their R&D investment fails.

China is currently undertaking efforts to introduce an emission trading system (ETS) to facilitate the growth of low-carbon industries. When an enterprise selects strategy j, its earnings from each vehicle produced within the ETS framework can be mathematically expressed as follows:

$$r_j = p\left(F - F_j\right) \tag{12}$$

where p represents the carbon price, F signifies the carbon quota allocated to the enterprise for vehicle production, and F_j denotes the life-cycle carbon emissions linked to vehicles produced under strategy j. It is essential to emphasize that the order of carbon quotas adheres to $F_2 > F > F_1$. In the wake of the introduction of the emissions trading market, enterprises that choose to produce traditional vehicles will receive negative returns, while those that choose to produce new energy vehicles will receive positive returns.

In China, enterprises involved in R&D endeavours receive tax incentives and fiscal subsidies; according to the tax law, this figure is 25%. The tax incentive is calculated as $T_s = 25\% \times (1 + l)c(\varphi)$.

Building upon the research of Chen et al. (2021), we determine the expected return of enterprises. P_{ij}^t represents the return of enterprise i, choosing strategy j at time t. The corresponding equations are defined in Eq. (13) and Eq. (14).

$$P_{i1}^t = (p_1 - c_1 + r_1) \times \frac{Q_c}{\theta_{i1}^t} - c(\varphi) + T_s \tag{13}$$

$$P_{i2}^t = (p_2 - c_2 + r_2) \times \frac{Q_t}{\theta_{i2}^t} \tag{14}$$

where Q_c represents the total demand for new energy vehicles among consumers at the current price level. The variables p_j, c_j, and r_j, denote the price, cost, and ETS revenue, respectively, for an enterprise adopting strategy j. Additionally, T_s denotes the tax incentives. The term $\frac{Q_c}{x_{i1}^t}$ characterizes the market share contributed by green consumers. $\frac{Q_t}{x_{i2}^t}$ represents the market share contributed by traditional consumers.

(2) Evolutionary Learning

In each simulation iteration, each enterprise agent calculates its own payoff, observes neighbouring agents' payoffs and adjusts its strategy accordingly. The probability that enterprise agent i imitates the strategy of neighbour j is shown in Eq. (15).

$$P_{i\to j} = \frac{1}{1 + \exp\left(\left(P_i - P_j\right)/k\right)} \tag{15}$$

Similar to consumer agents, enterprise agents also learn from their neighbours based on their income to update their strategies. As this study focuses on the impact of key factors in the diffusion system on the strategic evolution of both consumer and enterprise agents rather than the effects of the evolutionary mechanism on the system, the evolutionary mechanism at the enterprise level is set to be the same as that at the consumer level. In summary, the coevolution process of consumers and enterprises is shown in Fig. 3.

3.4. Model initialization

To initiate the simulation, relevant data from China's new energy vehicle industry are utilized to initialize the model parameters.

BYD New Energy, a prominent player in China's new energy vehicle market, has consistently maintained its top sales position for nine consecutive years. In 2021, BYD New Energy achieved sales of 603,000 new energy vehicles, capturing a market share of 17.1% (Fan et al., 2022). This performance makes BYD an ideal case study for China's new energy vehicle industry. The proportion of consumers who initially choose new energy vehicles is set to approximately 0.2. BYD specializes

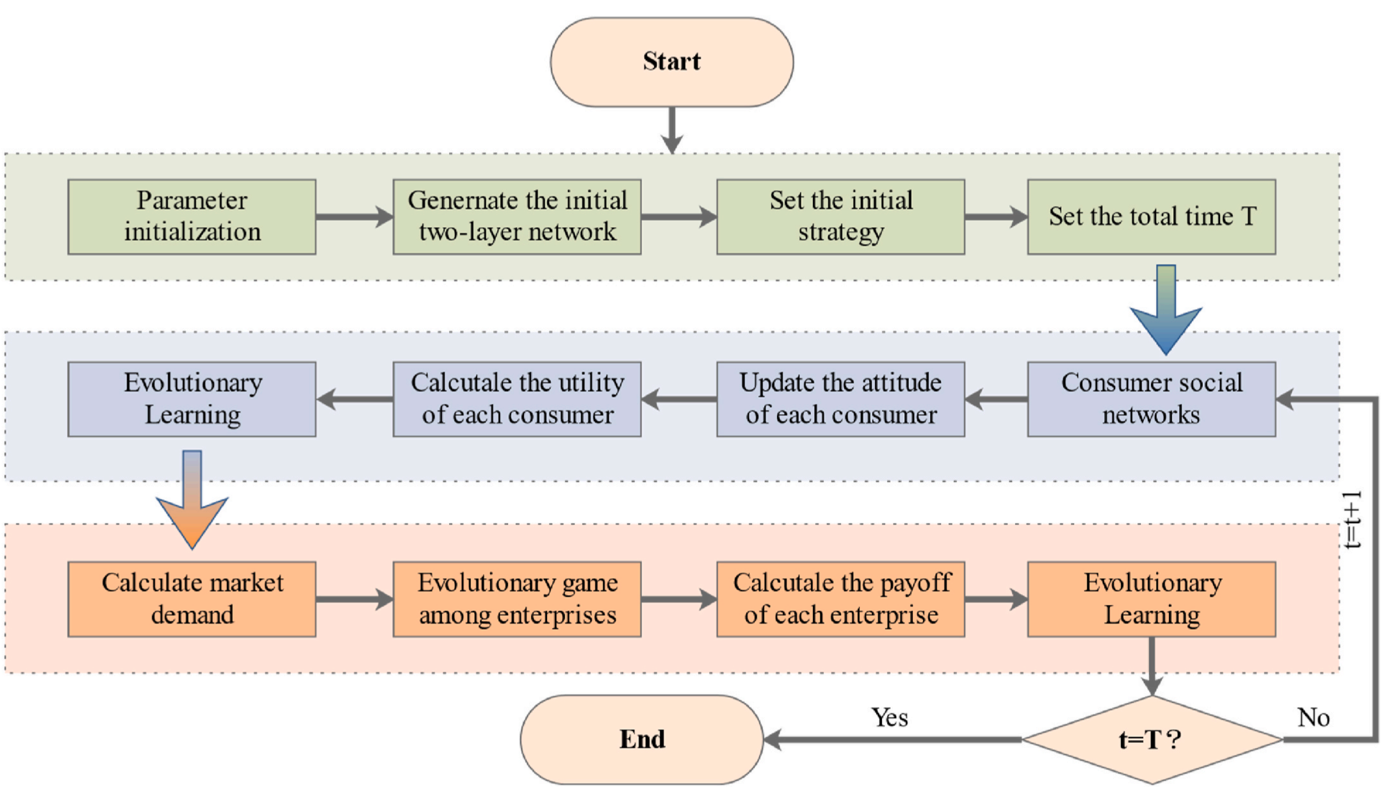

Fig. 3. Evolutionary process of multiagent evolution in a two-layer heterogeneous network.

in producing the 'Dynasty' series of new energy vehicles, with the most popular model in 2021 being priced at 210,000 CNY. By comparison, popular conventional vehicles such as the Ford Focus, Volkswagen Lavida and Toyota Corolla are priced at approximately 150,000 CNY. Therefore, the values of p_1 and p_2 are set to 210,000 and 150,000, respectively. An additional deduction coefficient of $l = 75\%$ is adopted following the research of Chen et al. (2021). According to the International Carbon Action Partnership, the 2021 ETS price in China was approximately 50 CNY/ton. Referring to the research of Wu et al. (2018), the lifecycle carbon emissions of a standard new energy vehicle and traditional vehicle are estimated to be approximately 20 tons and 30 tons, respectively. Therefore F_1 and F_2 are set to 20 and 30, respectively. According to existing research (Fan et al., 2022), F is set to 27 tons.

At the consumer level, the distance D_i travelled by each consumer follows a uniform distribution within the range of [15, 23], as studied by Ou et al. (2020). This range highlights the diversity of driving distances among consumers. According to a survey on consumer attitudes towards new energy vehicles conducted by Wu et al. (2023), the initial proportions of positive and negative attitudes towards new energy vehicles were 53.5% and 46.5%, respectively. Therefore, the proportion of consumers in favour of new energy vehicles is set to 55% in the initial state, which means $S_i = 1$ accounts for 55%. Based on the existing research on network evolution (Fan et al., 2022), k is set to 0.1. Additionally, a consumer network size of 1000 and an enterprise network size of 200 are assumed.

After setting the parameters, the model creates two-layer heterogeneous social networks representing consumers and enterprises. Initial strategies are randomly assigned to all agents, including attitudes and choices for consumers and production decisions for enterprises. To mitigate the potential effects of the initial policy distribution, 50 Monte Carlo simulations were performed for each experiment.

4. Results

4.1. The benchmark scenario for coevolution in the two-layer network

In the benchmark scenario, we assume that the parameter $\varphi = 0.4$ represents the probability of a successful transformation of green products. We performed 50 Monte Carlo simulations to explore the evolving dynamics of green product diffusion across consumer and enterprise networks. This benchmark scenario elucidates the micro mechanisms underlying the coevolution of new energy vehicles and serves as a comparative reference for subsequent experiments. The results of the coevolution of multiagent systems in a two-layer heterogeneous network are depicted in Fig. 4.

Fig. 4 (A) and 4 (C) illustrate the evolution of different strategies in the benchmark scenario. The shaded areas around the curves represent the 95% confidence intervals around the median values from 50 independent simulation runs. Initially, both consumers and enterprises have a choice of green products of approximately 20%. Over time, the adoption of green products gradually increases and reaches a steady state $T = 50$. The evolutionary paths of consumers and enterprises showed similar patterns. The spatial distributions of the strategies are shown in Fig. 4 (B) and 4 (D), where red and green nodes symbolize preferences for green and traditional products, respectively. Initially, 80% of the nodes are red. At $T = 10$, green nodes account for approximately 45%. When stability is reached, approximately 60% of the nodes are green, meaning that more than half of the agents chose green products.

The benchmark underscores the benefits of ABM in creating links between the micro and macro levels. Agents' decisions are not directly shaped by government policies; instead, they evolve through networking and learning mechanisms within the agent community. When policies align with agents' interests, agents embrace suitable strategies, illustrating a macrolevel reaction to governmental policies.

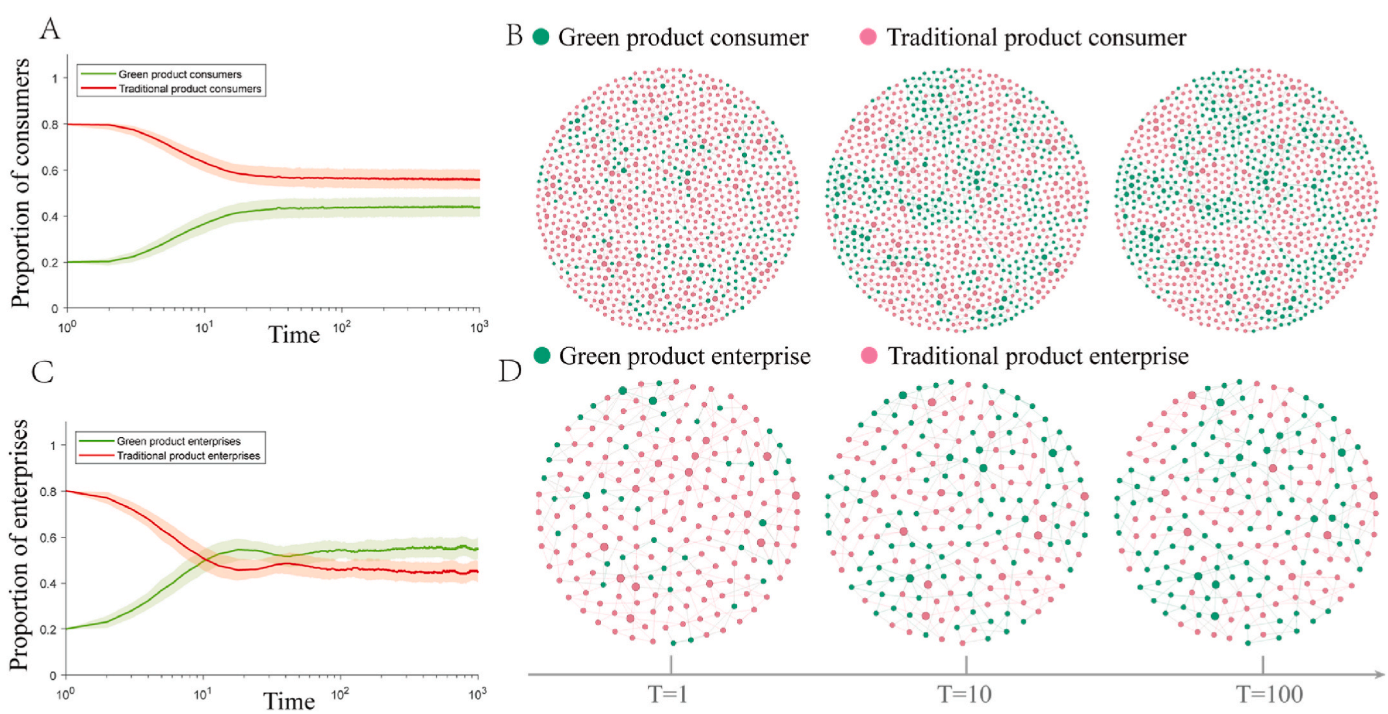

Fig. 4. The spatiotemporal dynamics of promotional strategies for green and traditional products. Panels (A) and (C) show the evolutionary trajectories of different strategies within consumer and enterprise networks. Panels (B) and (D) show snapshots of the 1000-node consumer agents and the 200-node enterprise agents at time points T = 1, 10, and 100. In these plots, red nodes represent agents who prefer traditional products, while green nodes represent agents who prefer green products within the network. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.2. Experiment 1: The impact of consumer subsidies on coevolution

First, we examine the impact of consumer subsidies on the promotion of green products, where consumer subsidies mainly target green products and there are asymmetric benefits in the industrial chain. Starting in 2023, the Chinese government no longer provided direct financial subsidies for the purchase of new energy electric vehicles; instead, it promoted consumer vouchers to indirectly reduce the purchase cost of new energy electric vehicles. These vouchers range from 2 thousand to 10 thousand CNY. To explore the effect of consumer subsidies on the diffusion of green products, we set subsidy levels at 2, 4, 6, 8 and 10 thousand CNY. The remaining parameters are consistent with the benchmark scenario. The results, which are presented in Fig. 5, show following: 1) Consumer subsidies have an encouraging effect on the promotion of green products, and 2) as subsidies increase, the encouraging effect on green products gradually weakens. Subsidies alter consumers' economic utility, attracting more consumers to adopt green products. However, with increasing subsidies, the effectiveness of green product dissemination gradually diminishes. This diminishing marginal utility is mainly attributed to consumer heterogeneity. Due to varying needs for driving distance, consumer subsidies can incentivize only consumers with midrange driving demands to purchase new energy vehicles. Benefit-sensitive consumers can swiftly change strategies, leaving the remaining consumers in need of higher levels of incentive to shift their strategies.

Consumer subsidies stimulate the purchase of green products from the demand side, thus driving the transformation and upgrading of green products on the enterprise side. Consumer subsidies can enhance the willingness of enterprises to undergo green transformation (Lee and Park, 2021; Shi et al., 2020; J. D. Zhao et al., 2021). Moderate subsidies can benefit producers while avoiding excessive inefficiencies. High subsidies can financially burden the government and increase the risk of subsidy misuse by enterprises (Li and Xie, 2021).

4.3. Experiment 2: The impact of government propaganda on coevolution

In addition to economic measures, the non-economic policies of governments also significantly influence the proliferation of green products, as noted by Encarnação et al. (2018) and Li et al. (2019). In Experiment 2, we focused on government propaganda and education to investigate the impact of nonfiscal policies on the diffusion of green products. B takes different values (−1, −0.5, 0, 0.5, and 1), and the remaining parameters are consistent with those in the benchmark scenario. The results shown in Fig. 6 indicate that the rate of green product diffusion decreases as B increases. In a state of evolutionary stability, the proportions of green product diffusion reach approximately 5%, 10%, 50%, 80% and 90%. Government propaganda and education alter consumer attitudes towards green products, thereby fuelling demand for them. This noneconomic factor accelerates the pace of green product diffusion, which align with the findings of Wang and Zheng (2019), whose research revealed that with an entirely green consumer base, the complete diffusion of green products can be achieved. Additionally Fan et al. (2022) suggested that driving green product adoption from the demand side is a relatively effective strategy for promoting consumer diffusion.

This experiment underscores the pivotal role of changes in attitude in propelling both the production and consumption of green products. Unlike subsidies, which exhibit diminishing marginal effects, or taxes, which sacrifice business profits, altering consumer attitudes remains vital. Therefore, authorities should prioritize nurturing environmental consciousness through measures such as environmental education. Indeed, governments and nongovernmental organizations are investing

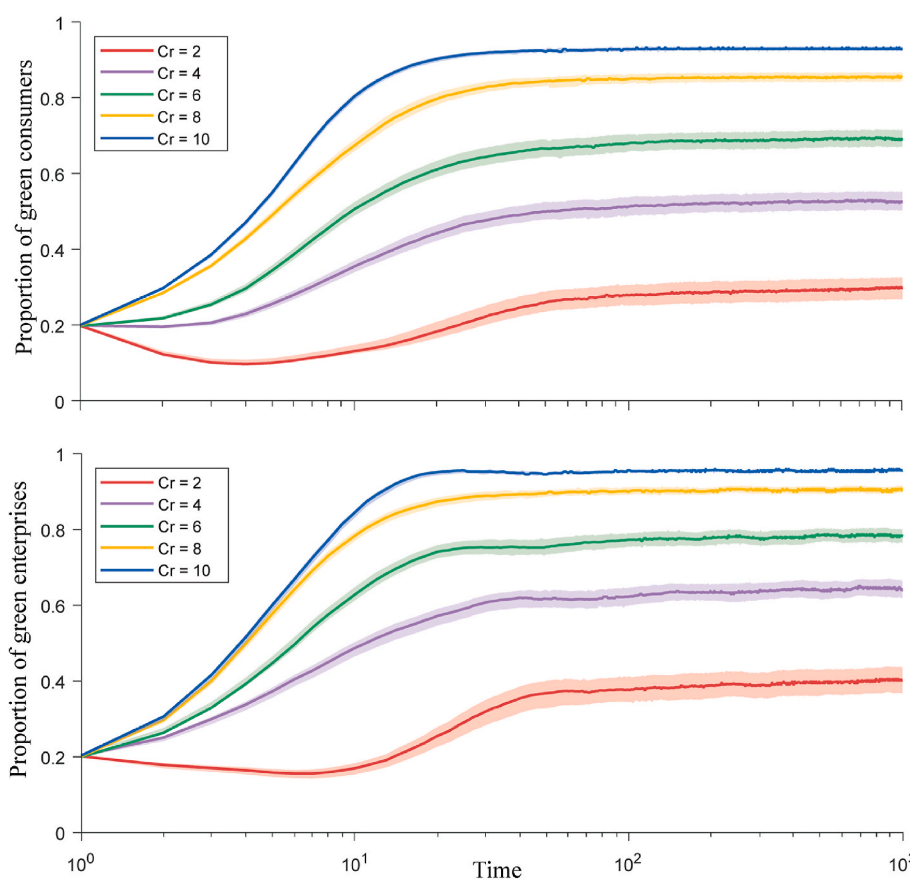

Fig. 5. The impact of consumer subsidies on the co-evolution of consumers and enterprises. The consumer-level dynamics are shown above; the enterprise-level dynamics are shown below.

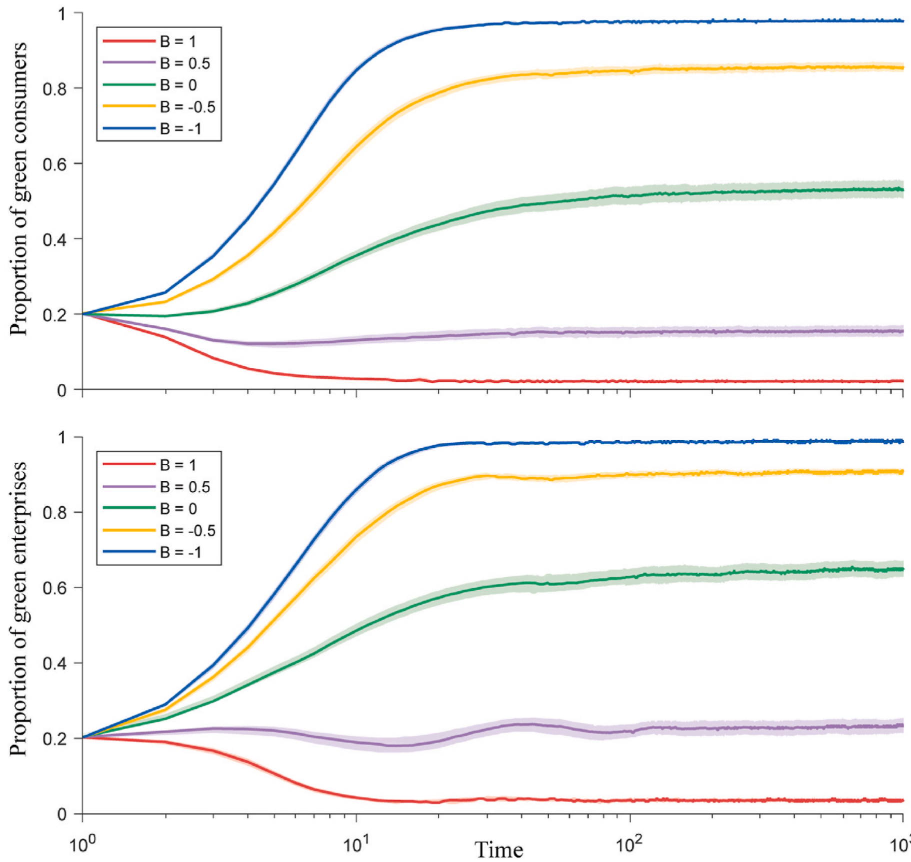

Fig. 6. The impact of government propaganda on the co-evolution of consumers and enterprises.

substantial resources in educating individuals about environmental awareness and consuming green products (Varela-Candamio et al., 2018; Briggs et al., 2019; Shi et al., 2021).

4.4. Experiment 3: The impact of carbon pricing on coevolution

Carbon pricing involves imposing charges on carbon dioxide emissions within ETSs, acting as a punitive measure for carbon emission control and gaining global attention since the early 2000s. To explore how carbon pricing influences the spread of green products among consumers and enterprises, various carbon pricing scenarios are studied: 0 CNY/ton, 50 CNY/ton (China), 350 CNY/ton (Norway), 500 CNY/ton (Finland), and up to 1,000 CNY/ton. Fig. 7 reveals two key findings: 1) As the carbon price increases, the diffusion rate of green products increases, and 2) the impact of carbon pricing on the enterprise level is more pronounced than that on the consumer level.

The first characteristic is related to enterprises transitioning towards producing green products to maximize profits. However, as the carbon pricing increases from 0 CNY/ton to 350 CNY/ton, the disparity among new energy vehicle manufacturers is only approximately 5% at equilibrium. This result suggests that new energy vehicle manufacturers are not particularly sensitive to low-carbon pricing. This finding aligns with the findings of Li et al. (2019) and Shi et al. (2021), who indicated that low levels of carbon pricing do not significantly enhance the diffusion of new energy vehicles. When the carbon price reaches higher levels, its impact on new energy vehicle diffusion becomes increasingly pronounced. Fig. 7 demonstrates that when the carbon price reaches 1,000 CNY/ton, the diffusion of new energy vehicles stabilizes at approximately 60%. The promotion of new energy vehicle production by enterprises under high carbon pricing can be attributed to their pursuit of profit. With demand for both traditional and green products fixed and adequately met by respective enterprises, carbon pricing compels traditional enterprises to transform and upgrade into green enterprises. As the number of traditional enterprises decreases, the production of each traditional product enterprise increases, leading to more carbon emissions. In this scenario, traditional enterprises endure substantial economic losses due to high carbon emission charges, further driving their transformation. The results suggest that carbon pricing might not be an effective emission reduction measure, as the impact of low carbon pricing can be negligible, while high carbon pricing results in profit losses. These outcomes are consistent with those of by Kaufman and Gordon (2018), H. Y. Dong et al. (2017), and Zhong et al. (2018).

The impact of carbon pricing on the enterprise level is more pronounced than that on the consumer level. Carbon pricing policies are directly implemented on enterprises, while consumers are indirectly affected by carbon pricing through the product chain, leading to a diffusion curve at the consumer level that is similar to that at the enterprise level. Furthermore, compared to usage costs and baseline pricing, carbon pricing has a relatively minor influence on the overall product price. Therefore, the diffusion curve at the consumer level is less affected by carbon pricing, and at low carbon pricing levels, it might even coincide with a scenario where no carbon pricing is in place. At high carbon pricing levels, the significant carbon cost primarily affects the production costs of traditional products at the enterprise level, prompting the transformation of green product production and the emergence of numerous green product manufacturers. This outcome subsequently lowers the purchasing costs of green products at the consumer level. However, using high carbon pricing to stimulate the diffusion of green products tends to be relatively inefficient, particularly at the consumer level.

Importantly, while very high carbon pricing can encourage the spread of green products among consumers and enterprises, the costs are considerable. Such pricing impacts enterprise profits and disrupts the market's inherent self-regulation. It is reasonable to speculate that if the

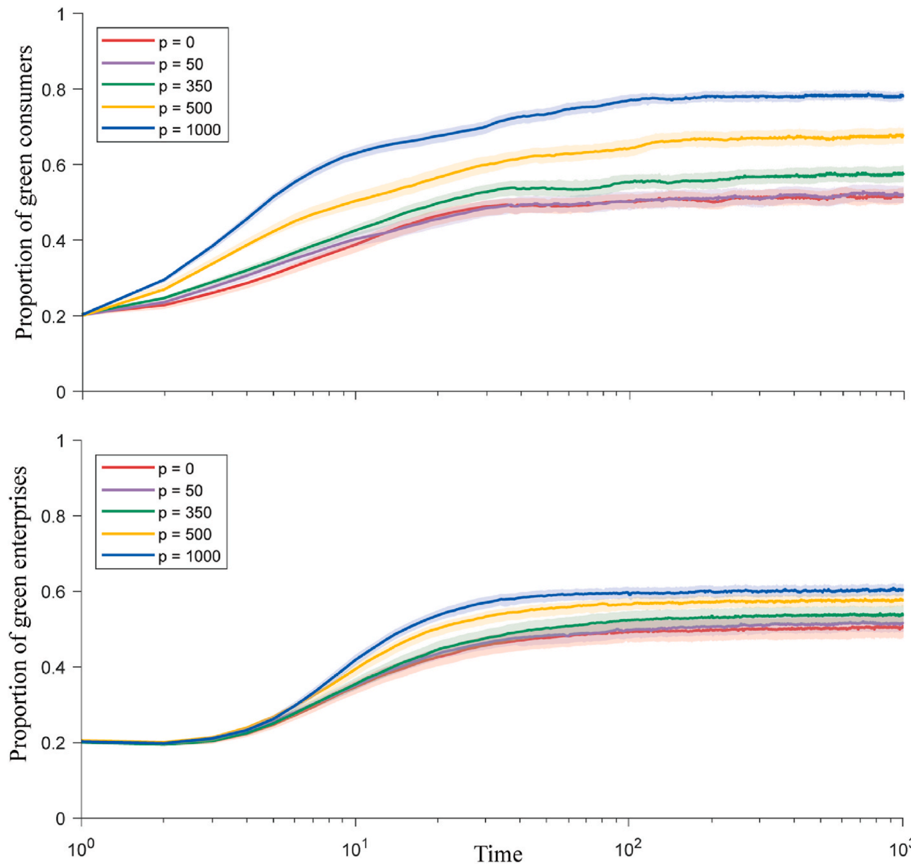

Fig. 7. The impact of carbon pricing on the co-evolution of consumers and enterprises.

model included an exit mechanism for enterprises, the market for traditional products would shrink to a level where manufacturers could sustain a minimum acceptable profit. Consequently, policy-makers should carefully consider the design of carbon pricing policies.

4.5. Sensitivity analyses of consumer subsidies, government propaganda and carbon pricing

To explore the influence of different factors on the diffusion of green products, we performed a sensitivity analysis of three factors, namely, consumer subsidies, government propaganda and carbon pricing. The results are shown in Fig. 8., where each box represents the results of 50 Monte Carlo simulations. Through previous experiments, we found that there is a similar evolutionary trend between consumers and enterprises; thus, so in this section, we choose consumers as a representative to discuss model sensitivity. The horizontal axis represents the number of consumer subsidies, which increases from 2,000 CNY to 6,000 CNY. *b* represents the intensity of government propaganda, as assumed in Experiment 2, with a negative value for the government propaganda of green products, and 0 representing no effect. *p* represents the price of carbon, which is verified for 0, 500 CNY/ton, and 1,000 CNY/ton. Through the analysis we can find that consumers are most sensitive to subsidies. Regardless of the combination of government propaganda and carbon pricing, consumer subsidies have the greatest impact on consumers' choice of green products, which is similar to our conclusion in Experiment 1 that consumer subsidies directly stimulate consumers' behaviour and directly affect their purchasing behaviour decisions. Government propaganda in different directions has different impacts on consumers' decisions. When the government chooses to publicize support for green products, there is a small increase in the choice of green products at the consumer level, but the impact is much smaller than that of consumer subsidies. In terms of carbon pricing, when the carbon price changes from 0 CNY/ton to 500 CNY/ton, consumers' choice of green products increases from a small extent, and when the carbon price changes from 500 CNY/ton to 1,000 CNY/ton, the proportion of consumers increases more significantly. Since there is a relationship between consumer demand and product supply, combining with Experiments 1, 2 and 3, we believe that a similar phenomenon occurs on the enterprise side. Therefore, we argue that consumer subsidies have the greatest impact on agents' choice of green products in this model.

5. Discussion

This study uses new energy vehicles as a case study to deepen the understanding of the synergistic co-evolution of green products between consumers and enterprises. We construct a two-layer network dynamics model. With this model, we empirically investigate the impact of various factors on the diffusion of green products, thereby offering directional guidance and a comprehensive understanding of the collaborative diffusion of green products.

Returning to the research question, we initially examine how strategic choices evolve within the benchmark scenario. In the context of two-layer networks, the evolution of green technology diffusion follows a distinct pattern: initial stability, subsequent growth, and eventual equilibrium. This microlevel mechanism emerges from complex social interactions. The effects of external policy changes take time to manifest, requiring extended social engagement to unfold. As early as 2009, the Chinese government launched the New Energy Vehicle Pilot City policy, elevating the strategic position of the new energy vehicle industry. The subsidy policy for China's new energy vehicle industry has undergone two consecutive five-year planning periods. With the development of the new energy vehicle market orientation, the role of industrial policies in promoting this industry has gradually weakened, shifting the focus towards technological support to foster independent innovation among

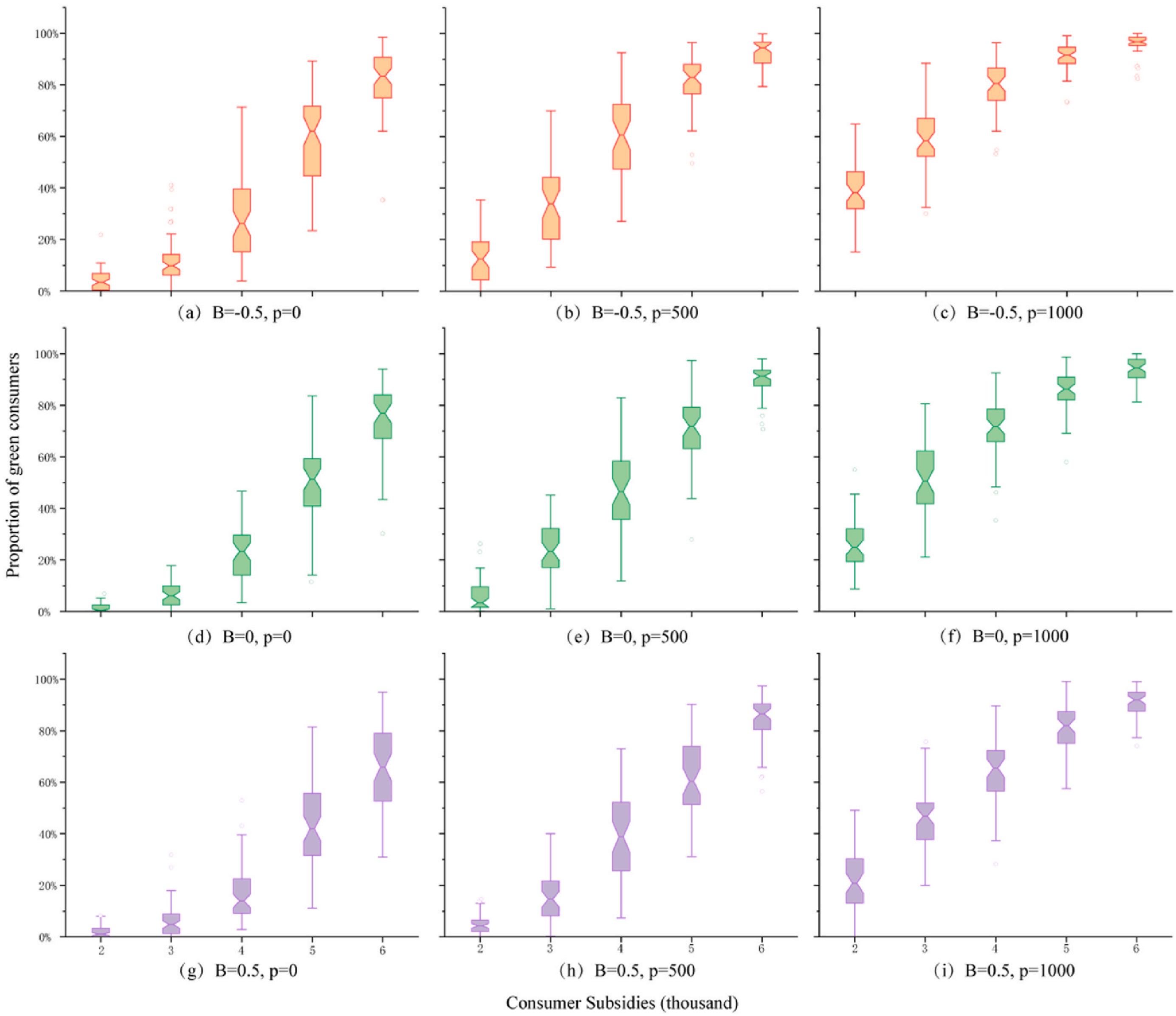

Fig. 8. The impact of different policies on consumer choices of green products. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

enterprises (Dong and Liu, 2020). Exploring the impact of new energy vehicle policies on the innovation activities of new energy vehicle enterprises and assessing the significance of policy effects are highly important.

Furthermore, the benchmark results and subsequent evolutionary trajectories demonstrate that consumer and enterprise strategies exhibit similar evolutionary trends. This result arises from the existence of supply and demand relationships that allow information to pass through different network layers. Specifically, consumers with a stronger inclination towards green consumption select green products, increasing the returns for green product manufacturers and attracting traditional enterprises to transform into green enterprises. As the number of green enterprises increases, the cost of producing green products decreases, thus providing incentives for consumers to choose these products. Additionally, under the influence of consumer social networks, the interaction between heterogeneous economic preferences and collective synergistic effects influences consumer strategy choices. Through multiple Monte Carlo simulations, we gain insights into the evolutionary paths of heterogeneous groups and summarize certain evolutionary trends. This application fully reflects the significance of research on complex systems, where ordered patterns emerge from the emergence of heterogeneous individuals.

Experiments 1 and 2 primarily simulate the impact of consumer-oriented policies. In Experiment 1, we investigate the impact of consumer subsidies on the promotion of new energy vehicles; such subsidies stimulate consumer purchases of new energy vehicles more directly and steadily than intervention policies for enterprises. Our findings are consistent with previous theoretical and empirical studies on the effects of economic incentives on new product promotion (Zhao et al., 2021). In Experiment 2, our study reveals that when the government's propaganda efforts for green products are relatively modest, consumers encounter difficulties in forming collective decisions to adopt such products. This finding is grounded in the influence of policies on consumer attitudes. In real-life contexts, only a minority of consumers are willing to embrace emerging products. Hence, when promoting green products, it becomes essential to simultaneously foster consumers' environmental consciousness (Awan et al., 2018), thereby impacting their decisions. Experiment 3 primarily simulated the impact of enterprise-oriented policies. Our research outcomes indicate that low-priced carbon pricing exerts minimal influence on the overall equilibrium proportions between traditional enterprises and green product enterprises. Furthermore, policies exhibit diminishing incentive effects as policy intensity escalates. Similar patterns of diminishing marginal effects have been observed in other studies (Chen et al., 2023b). Therefore, when formulating mandatory government policies, a certain policy intensity should be established to promote the diffusion of green products; it is also important to exercise prudence by setting upper limits to avoid excessive stimulation that could burden the government. In our sensitivity analysis, we found that consumer subsidies are more effective at promoting green products than government education and carbon pricing. In the promotion of new products, subsidies are often one of the best ways to promote consumer acceptance.

6. Conclusions and policy implications

In conclusion, this research delves into the intricate dynamics of green technology diffusion, recognizing the imperative role it plays in addressing severe environmental challenges. The slow pace of technology diffusion necessitates a nuanced understanding of the interplay between economic and social factors. Our study significantly contributes to the existing literature by elucidating the co-evolution of green technology diffusion, enterprises' strategies and consumers' attitudes within a dynamic system framework.

By integrating the Ising model and ABM theories, our novel model and controlled numerical experiments shed light on key insights. The initial experiment underscores the correlation between consumer subsidies and the facilitation of green technology diffusion. The second experiment highlights the government propaganda on coevolution. This experiment underscores the pivotal role of attitude change in propelling both the production and consumption of green products. Unlike subsidies that exhibit diminishing marginal effects or taxes that sacrifice business profits, altering consumer attitudes remains vital. Furthermore, our study reveals that carbon pricing plays a dual role in promoting the proliferation of green products. Lower carbon pricing has a minimal influence on the overall equilibrium proportions between traditional enterprises and green product enterprises. Higher carbon pricing can act as a catalyst for enterprise-level transformation, encouraging businesses to transition towards greener practices.

While our model provides valuable insights, it is an abstraction of real-world complexities. Future research may enhance this model by incorporating real data flows to more accurately model social relationships. Furthermore, this study specifically concentrates on the dynamic evolution of two types of agents, potentially overlooking the broader spectrum of entities involved in green product diffusion. For instance, different regions may be governed by distinct local policies, future investigations could delve into the inclusion of local government agents, building a three-layer interaction network model.

In terms of policy influence, this study underscores the imperative for policy-makers to carefully balance multifaceted interests. On the demand side, implementing subsidies is a straightforward and direct method for facilitating the diffusion of green products. Early-stage subsidies can swiftly propel products into the market. However, when subsidies surpass a certain threshold, excessive subsidization can not only lead to inefficient diffusion but also increase the fiscal burden and the misuse of subsidies by enterprises. It is essential for governments to regulate the usage of subsidies by enterprises, channelling them more effectively towards R&D and technology transfer and ensuring a more sustainable trajectory for the diffusion of green products. Policy-makers' investment in initiatives such as raising consumer environmental consciousness and educating the market about consuming low-carbon products holds paramount significance in driving the propagation of green products. Environmental education has proven to be an effective method of enhancing the public's environmental awareness and shaping attitudes towards low-carbon consumption. On the supply side, policy-makers must prudently weigh the benefits and drawbacks of implementing higher-level carbon pricing. Considering the effectiveness of high carbon pricing in promoting green product diffusion and the potential harm to enterprise enthusiasm, a comprehensive assessment of an industry's attributes before embarking on aggressive taxation policies is prudent. If governments prioritize achieving short-term carbon emission reduction goals within a relatively compressed timeframe, they can levy substantial carbon pricing on energy-intensive enterprises. Carbon pricing not only effectively promotes the diffusion of green products but also guides these companies towards long-term transformation. However, this measure hurts companies' short-term profits. Hence, policy-makers must exercise caution in implementing carbon pricing policies and determine a reasonable pricing range. Through sensitivity analysis, we find that among the three policies, increasing consumer subsidies is the most effective in promoting green products. Combining the results of experiments, we comprehensively find that demand-side stimuli have has a more significant effect on the promotion of green products than do supply-side stimuli. Policy-makers should pay more attention to the demand side to promote green products.

CRediT authorship contribution statement

Zhongjie Zhang: Writing – original draft, Data curation, Conceptualization. **Zhangang Han:** Writing – review & editing, Software, Methodology.

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.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the Funds of the National Natural Science Foundation of China [No. 62176022].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141689.

References

Alfarano, S., Lux, T., Wagner, F., 2005. Estimation of agent-based models: the case of an asymmetric herding model. Comput. Econ. 26, 19–49. https://doi.org/10.1007/s10614-005-6415-1.

Arvanitis, S., Ley, M., 2013. Factors determining the adoption of energy-saving technologies in Swiss firms: an analysis based on micro data. Environ. Resour. Econ. 54, 389–417. https://doi.org/10.1007/s10640-012-9599-6.

Awan, U., Kraslawski, A., Huiskonen, J., 2018. Governing interfirm relationships for social sustainability: the relationship between governance mechanisms, sustainable collaboration, and cultural intelligence. Sustainability 10, 4473. https://doi.org/10.3390/su10124473.

Axsen, J., Kurani, K.S., 2012. Social influence, consumer behavior, and low-carbon energy transitions. Annu. Rev. Environ. Resour. 37, 311–340. https://doi.org/10.1146/annurev-environ-062111-145049.

Ayres, I., Raseman, S., Shih, A., 2011. Evidence from two large field experiments that peer comparison feedback can reduce residential energy usage. SSRN Electron. J. https://doi.org/10.2139/ssrn.1858867.

Bass, F.M., 2004. Comments on "A new product growth for model consumer durables the Bass model.". Manag. Sci. 50, 1833–1840. https://doi.org/10.1287/mnsc.1040.0300.

Bass, F.M., 1969. A new product growth for model consumer durables. Manag. Sci. 15, 215–227. https://doi.org/10.1287/mnsc.15.5.215.

Bi, G., Jin, M., Ling, L., Yang, F., 2017. Environmental subsidy and the choice of green technology in the presence of green consumers. Ann. Oper. Res. 255, 547–568. https://doi.org/10.1007/s10479-016-2106-7.

Bollinger, B., Gillingham, K., 2012. Peer effects in the diffusion of solar photovoltaic panels. Market. Sci. 31, 900–912. https://doi.org/10.1287/mksc.1120.0727.

Bratanova, A., Robinson, J., Wagner, L., 2016. New technology adoption for Russian energy generation: what does it cost? A case study for Moscow. Appl. Energy 162, 924–939. https://doi.org/10.1016/j.apenergy.2015.10.102.

Briggs, L., Trautmann, N., Phillips, T., 2019. Exploring challenges and lessons learned in cross-cultural environmental education research. Eval. Progr. Plann. 73, 156–162. https://doi.org/10.1016/j.evalprogplan.2019.01.001.

Chen, F., Wu, B., Lou, W., 2021. An evolutionary analysis on the effect of government policies on green R & D of photovoltaic industry diffusion in complex network. Energy Pol. 152, 112217 https://doi.org/10.1016/j.enpol.2021.112217.

Chen, R., Fan, R., Wang, D., Yao, Q., 2023a. Exploring the coevolution of residents and recyclers in household solid waste recycling: evolutionary dynamics on a two-layer heterogeneous social network. Waste Manag. 157, 279–289. https://doi.org/10.1016/j.wasman.2022.12.030.

Chen, R., Fan, R., Yao, Q., Qian, R., 2023b. Evolutionary dynamics of homeowners' energy-efficiency retrofit decision-making in complex network. J. Environ. Manag. 326, 116849 https://doi.org/10.1016/j.jenvman.2022.116849.

Cialdini, R.B., Goldstein, N.J., 2004. Social influence: compliance and conformity. Annu. Rev. Psychol. 55, 591–621. https://doi.org/10.1146/annurev.psych.55.090902.142015.

Degirmenci, K., Breitner, M.H., 2017. Consumer purchase intentions for electric vehicles: is green more important than price and range? Transport. Res. Part Transp. Environ. 51, 250–260. https://doi.org/10.1016/j.trd.2017.01.001.

Degroot, M.H., 1974. Reaching a consensus. J. Am. Stat. Assoc. 69, 118–121. https://doi.org/10.1080/01621459.1974.10480137.

Diaz-Rainey, I., Ashton, J.K., 2015. Investment inefficiency and the adoption of eco-innovations: the case of household energy efficiency technologies. Energy Pol. 82, 105–117. https://doi.org/10.1016/j.enpol.2015.03.003.

Diaz-Rainey, I., Tzavara, D., 2012. Financing the decarbonized energy system through green electricity tariffs: a diffusion model of an induced consumer environmental market. Technol. Forecast. Soc. Change 79, 1693–1704. https://doi.org/10.1016/j.techfore.2012.05.012.

Dong, F., Liu, Y., 2020. Policy evolution and effect evaluation of new-energy vehicle industry in China. Resour. Pol. 67, 101655 https://doi.org/10.1016/j.resourpol.2020.101655.

Dong, H., Dai, H., Geng, Y., Fujita, T., Liu, Z., Xie, Y., Wu, R., Fujii, M., Masui, T., Tang, L., 2017. Exploring impact of carbon tax on China's CO 2 reductions and provincial disparities. Renew. Sustain. Energy Rev. 77, 596–603. https://doi.org/10.1016/j.rser.2017.04.044.

Dong, Y., Ding, Z., Martínez, L., Herrera, F., 2017. Managing consensus based on leadership in opinion dynamics. Inf. Sci. 397–398, 187–205. https://doi.org/10.1016/j.ins.2017.02.052.

Encarnação, S., Santos, F.P., Santos, F.C., Blass, V., Pacheco, J.M., Portugali, J., 2018. Paths to the adoption of electric vehicles: an evolutionary game theoretical approach. Transp. Res. Part B Methodol. 113, 24–33. https://doi.org/10.1016/j.trb.2018.05.002.

Fan, R., Bao, X., Du, K., Wang, Yuanyuan, Wang, Yitong, 2022. The effect of government policies and consumer green preferences on the R&D diffusion of new energy vehicles: a perspective of complex network games. Energy 254, 124316. https://doi.org/10.1016/j.energy.2022.124316.

Fan, R., Dong, L., Yang, W., Sun, J., 2017. Study on the optimal supervision strategy of government low-carbon subsidy and the corresponding efficiency and stability in the small-world network context. J. Clean. Prod. 168, 536–550. https://doi.org/10.1016/j.jclepro.2017.09.044.

Frederiks, E.R., Stenner, K., Hobman, E.V., 2015. Household energy use: applying behavioural economics to understand consumer decision-making and behaviour. Renew. Sustain. Energy Rev. 41, 1385–1394. https://doi.org/10.1016/j.rser.2014.09.026.

Galam, S., 1997. Rational group decision making: a random field Ising model at T = 0. Phys. Stat. Mech. Its Appl. 238, 66–80. https://doi.org/10.1016/S0378-4371(96)00456-6.

García-Maroto, I., García-Maraver, A., Muñoz-Leiva, F., Zamorano, M., 2015. Consumer knowledge, information sources used and predisposition towards the adoption of wood pellets in domestic heating systems. Renew. Sustain. Energy Rev. 43, 207–215. https://doi.org/10.1016/j.rser.2014.11.004.

Gifford, R., Nilsson, A., 2014. Personal and social factors that influence pro-environmental concern and behaviour: a review: personal and social factors that influence pro-environmental behaviour. Int. J. Psychol. https://doi.org/10.1002/ijop.12034 n/a-n/a.

Grabowski, A., Kosiński, R.A., 2006. Ising-based model of opinion formation in a complex network of interpersonal interactions. Phys. Stat. Mech. Its Appl. 361, 651–664. https://doi.org/10.1016/j.physa.2005.06.102.

Heinz, B., Graeber, M., Praktiknjo, A.J., 2013. The diffusion process of stationary fuel cells in a two-sided market economy. Energy Pol. 61, 1556–1567. https://doi.org/10.1016/j.enpol.2013.06.095.

Hojnik, J., Ruzzier, M., Fabri, S., Klopčič, A.L., 2021. What you give is what you get: willingness to pay for green energy. Renew. Energy 174, 733–746. https://doi.org/10.1016/j.renene.2021.04.037.

Hu, Y., Wang, Z., Li, X., 2020. Impact of policies on electric vehicle diffusion: an evolutionary game of small world network analysis. J. Clean. Prod. 265, 121703 https://doi.org/10.1016/j.jclepro.2020.121703.

Huang, S., Du, P., Hong, Y., Wu, W., 2023. Are corporate environmental, social, and governance practices contagious? The peer-effect perspective. Energy Environ. 0958305X2311777. https://doi.org/10.1177/0958305X231177749.

Ising, E., 1925. Beitrag zur Theorie des Ferromagnetismus. Z. Phys. 31, 253–258. https://doi.org/10.1007/BF02980577.

Islam, T., 2014. Household level innovation diffusion model of photo-voltaic (PV) solar cells from stated preference data. Energy Pol. 65, 340–350. https://doi.org/10.1016/j.enpol.2013.10.004.

Iyer, G., Soberman, D.A., 2016. Social responsibility and product innovation. Market. Sci. 35, 727–742. https://doi.org/10.1287/mksc.2015.0975.

Kaufman, N., Gordon, K., 2018. The Energy, Economic, and Emissions Impacts of a Federal US Carbon Tax. Glob. Energy Policy Columbia Univ. N. Y. NY Cent.

Kelchtermans, S., Neicu, D., Teirlinck, P., 2020. The role of peer effects in firms' usage of R&D tax exemptions. J. Bus. Res. 108, 74–91. https://doi.org/10.1016/j.jbusres.2019.09.059.

Kleinberg, J.M., 2000. Navigation in a small world. Nature 406. https://doi.org/10.1038/35022643, 845–845.

Laciana, C.E., Rovere, S.L., 2011. Ising-like agent-based technology diffusion model: adoption patterns vs. seeding strategies. Phys. Stat. Mech. Its Appl. 390, 1139–1149. https://doi.org/10.1016/j.physa.2010.11.006.

Leary, M.T., Roberts, M.R., 2010. Do peer firms affect corporate financial policy? SSRN electron. https://doi.org/10.2139/ssrn.1623379.

Lee, S.-H., Park, C.-H., 2021. Environmental regulations in private and mixed duopolies: taxes on emissions versus green R&D subsidies. Econ. Syst. 45, 100852 https://doi.org/10.1016/j.ecosys.2020.100852.

Li, F., Cao, X., Ou, R., 2021. A network-based evolutionary analysis of the diffusion of cleaner energy substitution in enterprises: the roles of PEST factors. Energy Pol. 156 https://doi.org/10.1016/j.enpol.2021.112385.

Li, J., Jiao, J., Tang, Y., 2019. An evolutionary analysis on the effect of government policies on electric vehicle diffusion in complex network. Energy Pol. 129, 1–12. https://doi.org/10.1016/j.enpol.2019.01.070.

Li, M., Gao, X., 2022. Implementation of enterprises' green technology innovation under market-based environmental regulation: an evolutionary game approach. J. Environ. Manag. 308, 114570 https://doi.org/10.1016/j.jenvman.2022.114570.

Li, Y., Shang, Y., Yang, Y., 2017. Clustering coefficients of large networks. Inf. Sci. 382–383, 350–358. https://doi.org/10.1016/j.ins.2016.12.027.

Li, Y., Xie, T., 2021. The influence of fiscal subsidy on the innovation behavior of manufacturing enterprises under the background of "the belt and road.". Proc. Bus. Econ. Stud. 4 https://doi.org/10.26689/pbes.v4i1.1661.

Li, Z., Zhu, H., Meng, Q., Shen, P., 2018. Green product competition-diffusion considering consumer network. Syst. Eng. 36, 106–112.

Mahajan, V., Muller, E., Bass, F.M., 1995. Diffusion of new products: empirical generalizations and managerial uses. Market. Sci. 14, G79–G88. https://doi.org/10.1287/mksc.14.3.G79.

Mahajan, V., Muller, E., Bass, F.M., 1990. New product diffusion models in marketing: a review and directions for research. J. Market. 54, 1–26. https://doi.org/10.1177/002224299005400101.

Natalini, D., Bravo, G., 2013. Encouraging sustainable transport choices in American households: results from an empirically grounded agent-based model. Sustainability 6, 50–69. https://doi.org/10.3390/su6010050.

Nolan, J.M., Schultz, P.W., Cialdini, R.B., Goldstein, N.J., Griskevicius, V., 2008. Normative social influence is underdetected. Pers. Soc. Psychol. Bull. 34, 913–923. https://doi.org/10.1177/0146167208316691.

Noll, D., Dawes, C., Rai, V., 2014. Solar Community Organizations and active peer effects in the adoption of residential PV. Energy Pol. 67, 330–343. https://doi.org/10.1016/j.enpol.2013.12.050.

Ou, S., Yu, R., Lin, Z., Ren, H., He, X., Przesmitzki, S., Bouchard, J., 2020. Intensity and daily pattern of passenger vehicle use by region and class in China: estimation and implications for energy use and electrification. Mitig. Adapt. Strategies Glob. Change 25, 307–327. https://doi.org/10.1007/s11027-019-09887-0.

Pabjan, B., 2004. The use of models in sociology. Phys. Stat. Mech. Its Appl. 336, 146–152. https://doi.org/10.1016/j.physa.2004.01.019.

Perc, M., Gómez-Gardeñes, J., Szolnoki, A., Floría, L.M., Moreno, Y., 2013. Evolutionary dynamics of group interactions on structured populations: a review. J. R. Soc. Interface 10, 20120997. https://doi.org/10.1098/rsif.2012.0997.

Prayoga, I.M.S., Adiyadnya, M.S.P., Putra, B.N.K., 2020. Green awareness effect on consumers' purchasing decision. Asia Pac. Manag. Bus. Appl. 8, 199–208. https://doi.org/10.21776/ub.apmba.2020.008.03.4.

Radomes, A.A., Arango, S., 2015. Renewable energy technology diffusion: an analysis of photovoltaic-system support schemes in Medellín, Colombia. J. Clean. Prod. 92, 152–161. https://doi.org/10.1016/j.jclepro.2014.12.090.

Rai, V., Robinson, S.A., 2013. Effective information channels for reducing costs of environmentally- friendly technologies: evidence from residential PV markets. Environ. Res. Lett. 8, 014044 https://doi.org/10.1088/1748-9326/8/1/014044.

Rixen, M., Weigand, J., 2013. AGENT-BASED simulation of consumer demand for smart metering tariffs. Int. J. Innovat. Technol. Manag. 10, 1340020 https://doi.org/10.1142/S0219877013400208.

Roca, C.P., Cuesta, J.A., Sánchez, A., 2009. Evolutionary game theory: temporal and spatial effects beyond replicator dynamics. Phys. Life Rev. 6, 208–249. https://doi.org/10.1016/j.plrev.2009.08.001.

Schlag, K.H., 1998. Why imitate, and if so, how? J. Econ. Theor. 78, 130–156. https://doi.org/10.1006/jeth.1997.2347.

Schnettler, S., 2009. A structured overview of 50 years of small-world research. Soc. Netw. 31, 165–178. https://doi.org/10.1016/j.socnet.2008.12.004.

Schultz, P.W., Nolan, J.M., Cialdini, R.B., Goldstein, N.J., Griskevicius, V., 2018. The constructive, destructive, and reconstructive power of social norms: reprise. Perspect. Psychol. Sci. 13, 249–254. https://doi.org/10.1177/1745691617693325.
Shi, Y., Han, B., Zeng, Y., 2020. Simulating policy interventions in the interfirm diffusion of low-carbon technologies: an agent-based evolutionary game model. J. Clean. Prod. 250, 119449 https://doi.org/10.1016/j.jclepro.2019.119449.
Shi, Y., Wei, Z., Shahbaz, M., Zeng, Y., 2021. Exploring the dynamics of low-carbon technology diffusion among enterprises: an evolutionary game model on a two-level heterogeneous social network. Energy Econ. 101, 105399 https://doi.org/10.1016/j.eneco.2021.105399.
Silvia, C., Krause, R.M., 2016. Assessing the impact of policy interventions on the adoption of plug-in electric vehicles: an agent-based model. Energy Pol. 96, 105–118. https://doi.org/10.1016/j.enpol.2016.05.039.
Suki, Mohd, Norazah, Suki, Mohd, Norbayah, Azman, N.S., 2016. Impacts of corporate social responsibility on the links between green marketing awareness and consumer purchase intentions. Procedia Econ. Finance 37, 262–268. https://doi.org/10.1016/S2212-5671(16)30123-X.
Tian, Z., Tian, Y., Chen, Y., Shao, S., 2020. The economic consequences of environmental regulation in China: from a perspective of the environmental protection admonishing talk policy. Bus. Strat. Environ. 29, 1723–1733. https://doi.org/10.1002/bse.2464.
Travers, J., Milgram, S., 1977. An experimental study of the small world problem. In: Social Networks. Elsevier, pp. 179–197. https://doi.org/10.1016/B978-0-12-442450-0.50018-3.
Usha Rao, K., Kishore, V.V.N., 2009. Wind power technology diffusion analysis in selected states of India. Renew. Energy 34, 983–988. https://doi.org/10.1016/j.renene.2008.08.013.
Varela-Candamio, L., Novo-Corti, I., García-Álvarez, M.T., 2018. The importance of environmental education in the determinants of green behavior: a meta-analysis approach. J. Clean. Prod. 170, 1565–1578. https://doi.org/10.1016/j.jclepro.2017.09.214.
Wang, J., Zhao, L., Zhu, R., 2022. Peer effect on green innovation: evidence from 782 manufacturing firms in China. J. Clean. Prod. 380, 134923 https://doi.org/10.1016/j.jclepro.2022.134923.
Wang, L., Zheng, J., 2019. Research on low-carbon diffusion considering the game among enterprises in the complex network context. J. Clean. Prod. 210, 1–11. https://doi.org/10.1016/j.jclepro.2018.10.297.
Wang, N., Tang, L., Pan, H., 2018. Analysis of public acceptance of electric vehicles: an empirical study in Shanghai. Technol. Forecast. Soc. Change 126, 284–291. https://doi.org/10.1016/j.techfore.2017.09.011.
Weisbuch, G., Boudjema, G., 1999. Dynamical aspects in the adoption of agri-environmental measures. Adv. Complex Syst. 2, 11–36. https://doi.org/10.1142/S0219525999000035.
Wu, B., Liu, P., Xu, X., 2017. An evolutionary analysis of low-carbon strategies based on the government–enterprise game in the complex network context. J. Clean. Prod. 141, 168–179. https://doi.org/10.1016/j.jclepro.2016.09.053.
Wu, Z., He, Q., Li, J., Bi, G., Antwi-Afari, M.F., 2023. Public attitudes and sentiments towards new energy vehicles in China: a text mining approach. Renew. Sustain. Energy Rev. 178, 113242 https://doi.org/10.1016/j.rser.2023.113242.
Wu, Z., Wang, M., Zheng, J., Sun, X., Zhao, M., Wang, X., 2018. Life cycle greenhouse gas emission reduction potential of battery electric vehicle. J. Clean. Prod. 190, 462–470. https://doi.org/10.1016/j.jclepro.2018.04.036.
Xiao, W., Xu, Y., 2012. The impact of royalty contract revision in a multistage strategic R&D alliance. Manag. Sci. 58, 2251–2271. https://doi.org/10.1287/mnsc.1120.1552.
Xiong, F., Liu, Y., Wang, L., Wang, X., 2017. Analysis and application of opinion model with multiple topic interactions. Chaos Interdiscip. J. Nonlinear Sci. 27, 083113 https://doi.org/10.1063/1.4998736.
Xiong, H., Payne, D., Kinsella, S., 2016. Peer effects in the diffusion of innovations: theory and simulation. J. Behav. Exp. Econ. 63, 1–13. https://doi.org/10.1016/j.socec.2016.04.017.
Xu, X., He, P., Xu, H., Zhang, Q., 2017. Supply chain coordination with green technology under cap-and-trade regulation. Int. J. Prod. Econ. 183, 433–442. https://doi.org/10.1016/j.ijpe.2016.08.029.
Yang, M., Chen, H., Long, R., Sun, Q., Yang, J., 2022. How does government regulation promote green product diffusion in complex network? An evolutionary analysis considering supply side and demand side. J. Environ. Manag. 318, 115642 https://doi.org/10.1016/j.jenvman.2022.115642.
Young, H.P., 2011. The dynamics of social innovation. Proc. Natl. Acad. Sci. USA 108, 21285–21291. https://doi.org/10.1073/pnas.1100973108.
Yuyin, Y., Jinxi, L., 2018. The effect of governmental policies of carbon taxes and energy-saving subsidies on enterprise decisions in a two-echelon supply chain. J. Clean. Prod. 181, 675–691. https://doi.org/10.1016/j.jclepro.2018.01.188.
Zeng, B., Zhu, L., Yao, X., 2020. Policy choice for end-of-pipe abatement technology adoption under technological uncertainty. Econ. Modell. 87, 121–130. https://doi.org/10.1016/j.econmod.2019.07.012.
Zhang, L., Xue, L., Zhou, Y., 2019. How do low-carbon policies promote green diffusion among alliance-based firms in China? An evolutionary-game model of complex networks. J. Clean. Prod. 210, 518–529. https://doi.org/10.1016/j.jclepro.2018.11.028.
Zhang, T., Gensler, S., Garcia, R., 2011. A study of the diffusion of alternative fuel vehicles: an agent-based modeling approach *. J. Prod. Innovat. Manag. 28, 152–168. https://doi.org/10.1111/j.1540-5885.2011.00789.x.
Zhao, D., Ji, S., Wang, H., Jiang, L., 2021. How do government subsidies promote new energy vehicle diffusion in the complex network context? A three-stage evolutionary game model. Energy 230, 120899. https://doi.org/10.1016/j.energy.2021.120899.
Zhao, J., Jiang, Q., Dong, X., Dong, K., 2021. Assessing energy poverty and its effect on CO2 emissions: the case of China. Energy Econ. 97, 105191 https://doi.org/10.1016/j.eneco.2021.105191.
Zheng, J., Wang, J., Yu, L., 2022. How to improve the effectiveness of Chinese green certificate market? A complex network and social influence analysis. J. Clean. Prod. 380, 134943 https://doi.org/10.1016/j.jclepro.2022.134943.
Zhong, M., Liu, Q., Zeng, A., Huang, J., 2018. An effects analysis of China's metal mineral resource tax reform: a heterogeneous dynamic multi-regional CGE appraisal. Resour. Pol. 58, 303–313. https://doi.org/10.1016/j.resourpol.2018.05.020.