IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 18 June 2022, accepted 16 July 2022, date of publication 21 July 2022, date of current version 27 July 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3192838

RESEARCH ARTICLE

Greening, Pricing and Marketing Coordination for a Complex Three-Level Supply Chain Under the Carbon Tax in China

JIDONG GUO AND MENGHAO XI
School of Emergency Management, Institute of Disaster Prevention Science and Technology, Langfang 065201, China
Corresponding author: Jidong Guo (guojidong@cidp.edu.cn)

This work was supported in part by the Project of the National Natural Science Foundation of China under Grants 72021001, 72174019, and in part by the Fundamental Research Funds for Central Universities under Grant ZY20180229.

ABSTRACT This paper examines a complex supply chain consisting of a raw material manufacturer, a consumer goods fabricator, a retailer and an end user. A sequential decision game model is constructed under carbon tax regulation, considering multiparty green technology innovation and green product marketing efforts in the supply chain. Using a backward-induction analysis process, the Nash equilibria of the game are obtained. With the help of numerical simulation, the sensitivity analysis of the key parameters affecting system performance is carried out. We find the following results. (i) Carbon tax regulation brings about a new cost burden for supply chain members in different ways, with the largest impact being on the profit of the raw material manufacturer. (ii) The marginal emission reduction effect of carbon tax regulation shows a declining trend. The cost of greening efforts will exceed the carbon tax rate as it continues to rise. (iii) Customer demand is significantly affected by the footprint and energy efficiency of products and is much more relevant for energy efficiency than for footprint in the production phase.

INDEX TERMS Carbon tax, game, green technology renovation, simulation, supply chain.

I. INTRODUCTION

According to estimates by the Global Carbon Project, in 2021, global carbon emissions reached 36.4 billion tons, growing by 4.9% on a year-on-year basis, which is close to its highest level in 2019, the year just before the outbreak of coronavirus disease 2019 [1]. Among global carbon emissions, those of China account for approximately 30.49%, ranking first in the world [1]. China's energy conservation and emission reduction targets have attracted worldwide attention. As is known, China's urbanization is developing rapidly, and its economic development mode, which is mainly based on fossil energy, is difficult to change dramatically in the short term. However, although China is facing an increasingly acute contradiction between economic development and carbon emission reduction, on September 22nd, 2020, at the 75th United Nations General Assembly, the country announced that it would strive to let its carbon dioxide emissions peak by 2030 and to achieve the goal of carbon neutrality by 2060 [2]. This announcement shows China's strong will to fully promote the new development concept and its willingness to make further contributions to the global response to climate change.

The adjustment of a country's economic, industrial, and energy structures through macrocontrol is undoubtedly a vital way through which to achieve green economic development. However, at the microeconomic level, especially in the market economy, a market-oriented emission reduction mechanism to guide enterprises as market entities in carrying out carbon emission reduction and green technology innovation is recognized as the most market-efficient measure [3]. Carbon cap, carbon tax, carbon cap and trade, carbon offset, greening credit, etc., are all commonly used carbon emission reduction measures around the world, especially carbon tax and carbon cap-and-trade systems, which are considered the most market-oriented and effective mechanisms [4]. As one of the most common market-based carbon emission regulations, carbon taxes have been implemented in many countries,

The associate editor coordinating the review of this manuscript and approving it for publication was Alba Amato.

such as France, Sweden, Canada, Australia, and South Africa. Regarding the environment in which we live, including air, water, and soil, which are all public goods, carbon taxation on carbon emissions is considered a powerful policy tool to address climate change and promote green technology innovation [5]. Different from other types of enterprise innovation, green technology innovation is not the voluntary will of enterprises, and the green innovation of enterprises faces dual ''externalities'' [6], making it difficult for such an approach to truly become the core competitiveness of enterprises [7]. Therefore, the effective internalization of carbon emission costs is the key to formulating energy conservation and emission reduction policies [8]. Imposing a carbon tax on upstream enterprises, especially on upstream resource-based enterprises, can effectively control most carbon emissions [9]. In China, the national carbon market officially opened on July 16th, 2021. A total of 2,225 thermal power generation companies representing the power industry first entered the market to participate in transactions. In the future, more carbon-intensive industries will join the market. The carbon emission price formed in the national carbon market is an essential basis on which China can levy the carbon tax. One of the advantages of introducing a carbon tax is to promote the initiative internationally. Once other countries plan to levy a carbon tax, China can avoid paying a carbon tax at the border for its export products and reduce the impact of foreign policies on foreign trade exports [10], [11]. In addition to research on the design of the carbon tax system and the impact of the carbon tax on the macroeconomy and industry in the above economic fields, research on the impact of the carbon tax on supply chain emission reduction and green technology innovation has also been a hot topic in the past ten years.

Benjaarfar *et al.* were the first to introduce the concept of carbon footprint into the supply chain optimization model, analyzing how supply chain companies can make pricing decisions by adjusting their order quantity and output under different carbon emission reduction policies to maximize overall supply chain performance [12]. In addition to carbon regulations, the motivation for carbon emission reduction or green technology innovation in the supply chain is the evolution of market demand preferences, especially the improvement of consumers' awareness of environmental protection. People are also increasingly inclined to pay higher prices for products with lower carbon footprints [13]–[16]. Li *et al.* believed that in the context of stricter carbon regulations, consumers are paying increasing attention to the carbon emission factors of products. Their research discussed how to make decisions on product output and carbon emission reduction efforts with two types of carbon regulations, namely, absolute cap and intensity cap, in the context of a simple single-level supply chain [17]. Yu *et al.* hypothesized that product demand is related to its carbon emission reduction level and that the carbon emission reduction level is continuously evolving according to a given linear differential equation. Based on differential game theory, the joint emission reduction efforts, pricing strategies, and optimal emissions for both parties in the supply chain are obtained, the results of which show that both parties in the supply chain can achieve a win-win situation in terms of both supply chain benefits and ecology [18]. Swami and Shah considered the problem of the coordination of a manufacturer and a retailer in a vertical supply chain, addressing some pertinent questions in this regard, such as those related to the extent of efforts in greening operations by manufacturers or retailers, the level of cooperation between the two parties, and how to coordinate their operations in a supply chain. The above authors found that greening efforts by the manufacturer and retailer would result in demand expansion at the retail end [19]. In addition to supply chain contract coordination and upstream and downstream member game models, researchers have also studied the optimization of supply chain strategic planning models under carbon tax regulation [12], [20]. In addition to the carbon tax, researchers have also studied the impact of other carbon emission reduction policies on optimal supply chain operations. For example, [21], [22] studied the game problem of upstream and downstream members of the supply chain under the carbon cap-and-trade schema and obtained the optimal carbon emission level and profit distribution mechanism among game players. Yuan *et al.* studied how the government provides subsidies for carbon emission reduction and how it affects the optimal level of carbon emissions in the supply chain and the level of green product marketing efforts [23]. An *et al.*, under the hard constraints of carbon emissions in the supply chain, studied how to design a green credit financing model to reduce manufacturers' carbon emissions and improve supply chain performance [24]. In the context of carbon emission reduction policies, some researchers have studied different network structures of supply chains [19], [25], [26], differences in member voices [27], different network optimization problems [28], [29] and other perspectives. Many meaningful studies have been carried out on a single-level supply chain, that is, including a supplier and a manufacturer or a manufacturer and a logistics service provider.

However, in reality, the supply chain network is often complex and multilayered, and the carbon emissions of each member are highly uneven, being mainly concentrated in the upstream raw material manufacturing enterprises of the supply chain. In contrast, downstream enterprises produce end products for customers and are responsible for product marketing and promotion, such as manufacturing typical automobile, computer, communication and consumer electronics. The present research re-examines the collaborative relationship between supply chain members, builds a model that is more in line with reality, and seeks pricing and emission reduction decisions made by multiple parties to maximize their individual interests.

The remainder of the paper is organized as follows. Based on rational assumptions and notations, a multilevel supply chain with coordinated green renovation and marketing efforts, regulated by carbon tax policy, is established in Section II. In Section III, backward-induction analysis is applied to obtain the Nash equilibria of the game model as mentioned above. Subsequently, in Section IV, due to complexity in the form of the equilibria, numerical simulation is carried out to observe the relations between supply chain performance and the key parameters for the supply chain, and a discussion is presented. In the last section, Section V, the research is concluded; the main findings and limitations are given, and future research avenues are also proposed.

II. MULTILEVEL SUPPLY CHAIN GREEN INNOVATION GAME MODEL

The theoretical model proposed in this study is derived from the simulation of realistic supply chain scenarios. We assume that there is such a supply chain for automobile, computer, communication and consumer electronics in the market. The most upstream enterprise is a steel or nonferrous metal smelting and processing enterprise, called a raw material manufacturer, and the downstream enterprise is an automobile, computer, communication or consumer electronics fabricator, whose products are final products, which can meet the needs of consumers. The closest to the consumer is the sales terminal, called the retailer, and, finally, the end consumer. The overall supply chain is a value-added chain. Each enterprise makes different contributions to the promotion of the consumption of green products and transmits their respective costs downstream through product pricing decisions. Customer demand has multiple sensitivities not only to the price of greener products but also to the carbon footprint, the level of energy efficiency of the product, and the degree of marketing efforts. A schematic diagram of this theoretical model is shown in Fig. 1.

The whole game process is as described in Fig. 1. First, the raw material manufacturer determines the investment in the carbon emission reduction and sales price of its raw material products. The final product fabricator determines the product energy efficiency level and its sales pricing. Finally, the retailer determines its advertising and marketing inputs and final product retail price. This process is a three-stage sequential game. The standard solution is to use the backward-induction analysis technique to solve the problem, that is, to first find the retailer's strategy and then iterate upward, layer by layer, to find the strategy of all members of the entire supply chain. The underlying theoretical assumptions of this model include the following:

$H1$: Market demand is equal to the quantity traded between upstream and downstream members of the supply chain.

$H2$: In the supply chain, a product provided by an upstream enterprise is just enough to lead to a downstream enterprise producing a product.

$H3$: There is a quadratic relationship between investment in green technology innovation and the carbon emission reduction level (also called the degree of greening).

$H4$: There is a quadratic relationship between investment in energy efficiency improvement and the energy efficiency improvement level.

$H5$: There is a diminishing marginal return effect between a retailer's marketing effort and market demand.

TABLE 1. Symbolic conventions of variables and parameters.

Symbol	Connotation
w_s	Raw material procurement cost for the raw material manufacturer
m_s	Marginal production cost for the raw material manufacturer
m_f	Marginal production cost for the final product fabricator
m_r	Retailer's marginal cost of sales
c_{s0}	Initial marginal carbon emissions for the raw material manufacturer
c_s	Carbon emission reduction level per unit of goods for the raw material manufacturer
μ	Emission reduction (green innovation) cost factor for the raw material manufacturer
p_s	Raw material product sales price
e_{f0}	Final product fabricator's initial energy efficiency ratio per unit of product
e_f	Final product fabricator's unit product energy efficiency ratio improvement
ν	Improvement (technological innovation) cost factor for the final product fabricator
p_f	Final product fabricators sales price
A	Retailers marketing input
p_r	Retailers retail price
$\hat{Q}$	Basic demand
τ	Unit carbon emission tax rate
α	Price elasticity of demand
γ	Marketing effect coefficient of demand
λ	Carbon footprint elasticity of demand
ρ	Energy efficiency elasticity of demand

$H6$: There is a linearly proportional relationship between market demand and the carbon footprint per unit product.

$H7$: There is a linearly proportional relationship between market demand and product energy efficiency.

$H8$: There is a quadratic root relationship between market demand and a retailer's marketing investment.

With the above assumptions, it is also necessary to make symbolic conventions for the parameters and variables used in the model, as shown in Table 1. According to the notation conventions, some endogenous variables can be obtained as follows.

According to the notation conventions, some endogenous variables can be obtained as follows.

The investment in emission reduction is $I_s = \frac{1}{2}\mu {c_s}^2$ for the raw material manufacturer in the current period. The energy efficiency improvement investment is $I_f = \frac{1}{2}\nu {e_f}^2$ of the final product fabricator.

Let carbon footprint $c = c_{s0} - c_s$ and energy efficiency ratio $e = e_{f0} + e_f$; then, we obtain the customer purchased quality as follows:

$$Q = \hat{Q} - \alpha p_r + \gamma\sqrt{A} - \lambda c + \rho e \tag{1}$$

Various supply chain performance indicators can be chosen. Here, the profits for each member enterprise in the supply chain are used as follows:

The profit for the raw material manufacturer is

$$\Pi_s = Q(p_s - m_s - w_s) - \tau Q(c_{s0} - c_s) - I_s \tag{2}$$

The profit for the final product fabricator is

$$\Pi_f = Q(p_f - m_f - p_s) - I_f \tag{3}$$

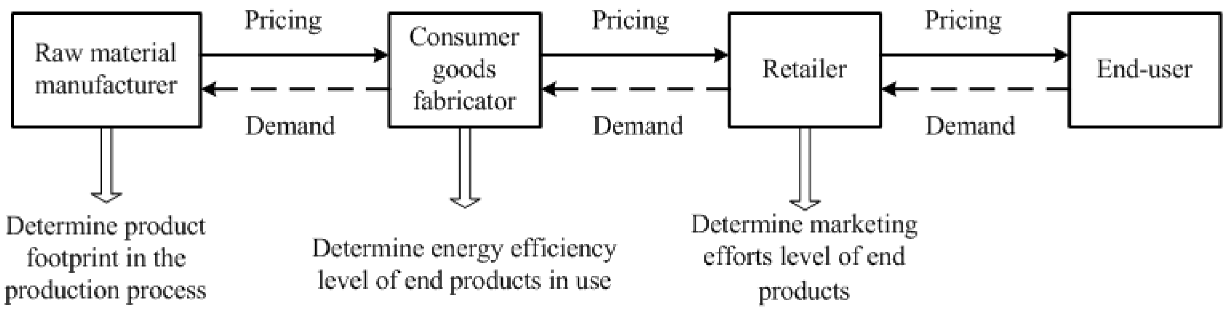

FIGURE 1. **Game relations among members in the supply chain.**

The profit for the retailer is

$$\Pi_r = Q(p_r - m_r - p_f) - A \tag{4}$$

The whole supply chain benefit is

$$\Pi = \Pi_s + \Pi_f + \Pi_r \tag{5}$$

III. NASH EQUILIBRIA ANALYSIS OF THE PROPOSED MODEL

In the previous section, a three-level complex supply chain model with four stakeholders is established. The model assumes that all supply chain members are rational, and its optimization goal is to obtain the greening strategy of raw material manufacturers, the energy efficiency reduction strategy of consumer goods manufacturers, and the marketing strategy of retailers. At the same time, it can be seen from the model that any party's strategy changes the benefits of the whole supply chain, as it bears all the costs of the implementation of the effort strategy but cannot obtain all the benefit changes brought about by it. That is, stakeholders in the supply chain need to observe each other's strategic choices and finally implement the most favorable strategy. This situation is obviously one of noncooperative competition in the supply chain. However, cooperation among supply chain members is inevitable. Only by increasing the sales of green products can all parties ensure that their own profits are improved. This kind of competition and cooperation game among members in the supply chain is obviously suitable for the use of game theory as a research tool.

The supply chain model has a potential assumption; that is, in the supply chain, upstream enterprises are always stronger than downstream enterprises. Raw material manufacturers are the most powerful enterprises in the whole supply chain, followed by consumer goods manufacturers, and retailers have the least power. The order of making decisions is also from upstream to downstream along the supply chain. This situation is an unequal sequential, or dynamic, game. Generally, the sequential game is solved by the backward-induction analysis technique, which means that in the decision-making process of the supply chain, the upstream enterprise is more powerful and can observe the strategy selection process and results of the downstream enterprise in response to its own strategy selection. Therefore, the upstream enterprise incorporates the best response of the downstream enterprise into its own profit function for optimal decision making. The following game analysis process follows the ideas described above.

First, the retailer's strategies must be obtained. By bringing Equation (1) into Equation (4), the profit function is expanded as follows:

$$\Pi_r = (\hat{Q} - \alpha p_r + \gamma\sqrt{A} - \lambda c + \rho e)(p_r - m_r - p_f) - A \tag{6}$$

For the variable A in Equation (6), the first- and second-order partial derivatives are obtained as follows:

$$\frac{\partial \Pi_r}{\partial A} = \frac{\gamma(p_r - m_r - p_f)}{2\sqrt{A}} - 1 \tag{7}$$

$$\frac{\partial^2 \Pi_r}{\partial A^2} = -\frac{\gamma(p_r - m_r - p_f)}{4A^{3/2}} \tag{8}$$

The partial derivatives of another variable, p_r, are put as follows:

$$\frac{\partial \Pi_r}{\partial p_r} = \hat{Q} - \alpha p_r + \gamma\sqrt{A} - \lambda c + \rho e - \alpha(p_r - m_r - p_f) \tag{9}$$

$$\frac{\partial^2 \Pi_r}{\partial {p_r}^2} = -2\alpha \tag{10}$$

Then, the second-order joint partial derivatives are found as follows:

$$\frac{\partial^2 \Pi_r}{\partial A \partial p_r} = \frac{\partial^2 \Pi_r}{\partial A \partial p_r} = \frac{\gamma}{2\sqrt{A}} \tag{11}$$

With all second-order partial derivatives being as above, one of the Hessian matrix conditions is given as follows:

$$H = \frac{\alpha\gamma(p_r - m_r - p_f)}{2A^{3/2}} - \frac{\gamma^2}{4A} > 0 \tag{12}$$

By simplifying Equation (12), we obtain

$$p_r - m_r - p_f > \frac{\gamma\sqrt{A}}{2\alpha} \tag{13}$$

Under the condition that Equation (13) is satisfied, let Equation (7) equal 0; then, we can obtain

$$p_r - m_r - p_f = \frac{2\sqrt{A}}{\gamma} \tag{14}$$

Combined with Equations (13) and (14), the Hessian matrix conditions are further simplified as follows:

$$4\alpha > \gamma^2 \tag{15}$$

By setting Equation (9) to 0, we obtain

$$\hat{Q} - \alpha p_r + \gamma\sqrt{A} - \lambda c + \rho e - \alpha(p_r - m_r - p_f) = 0 \tag{16}$$

Let

$$\overline{Q} = \hat{Q} - \lambda c + \rho e + \alpha(m_r + p_f) \tag{17}$$

Then, Equation (16) is simplified as follows:

$$\overline{Q} - 2\alpha p_r + \gamma\sqrt{A} = 0 \tag{18}$$

By combining Equations (14) and (18), the retailer's optimal response strategy can be obtained as follows:

$$p_r = \frac{2\overline{Q} - \gamma^2(m_r + p_f)}{4\alpha - \gamma^2} \tag{19}$$

$$A = \frac{\gamma^2(\overline{Q} - 2\alpha m_r - 2\alpha p_f)^2}{(4\alpha - \gamma^2)^2} \tag{20}$$

With the best responses of the retailer, we now start finding the strategies for the consumer goods fabricator.

Then, Equations (19) and (20) are added to the final product fabricator's profit function, that is, Equation (3), and we can obtain

$$\Pi_f = \frac{2\alpha(\hat{Q} - \lambda c + \rho e) - 2\alpha^2(m_r + p_f)}{4\alpha - \gamma^2}(p_f - m_f - p_s) - \frac{1}{2}\nu {e_f}^2 \tag{21}$$

First, Equation (21) is expanded as follows:

$$\Pi_f = \frac{2\alpha(\hat{Q} - \lambda c + \rho(e_{f0} + e_f)) - 2\alpha^2(m_r + p_f)}{4\alpha - \gamma^2} (p_f - m_f - p_s) - \frac{1}{2}\nu {e_f}^2 \tag{22}$$

Then, the first-order, second-order, and joint partial derivatives for all the decision variables in Equation (22) are calculated for the final product fabricator as follows:

$$\frac{\partial \Pi_f}{\partial p_f} = \frac{2\alpha(\hat{Q} - \lambda c + \rho(e_{f0} + e_f)) - 2\alpha^2(m_r + p_f)}{4\alpha - \gamma^2} - \frac{2\alpha^2}{4\alpha - \gamma^2}(p_f - m_f - p_s) = 0 \tag{23}$$

$$\frac{\partial^2 \Pi_f}{\partial {p_f}^2} = \frac{-4\alpha^2}{4\alpha - \gamma^2} < 0 \tag{24}$$

$$\frac{\partial \Pi_f}{\partial e_f} = \frac{2\alpha\rho(p_f - m_f - p_s)}{4\alpha - \gamma^2} - \nu e_f = 0 \tag{25}$$

$$\frac{\partial^2 \Pi_f}{\partial {e_f}^2} = -\nu < 0 \tag{26}$$

$$\frac{\partial^2 \Pi_f}{\partial p_f \partial e_f} = \frac{\partial^2 \Pi_f}{\partial e_f \partial p_f} = \frac{2\alpha\rho}{4\alpha - \gamma^2} \tag{27}$$

The extremum condition of the final product fabricators profit function can be obtained as follows:

$$H = \frac{4\nu\alpha^2}{4\alpha - \gamma^2} - \frac{4\alpha^2\rho^2}{(4\alpha - \gamma^2)^2} > 0 \tag{28}$$

By simplifying Equation (28), we can obtain

$$4\alpha - \gamma^2 > \frac{\rho^2}{\nu} \tag{29}$$

By putting Equations (23) and (25) into simultaneous equations, let

$$\overline{\overline{Q}} = \hat{Q} - \lambda c + \rho e_{f0} + \alpha(m_f + p_s - m_r) \tag{30}$$

The final product fabricators best responses are as follows:

$$p_f = \frac{\overline{\overline{Q}}\nu(4\alpha - \gamma^2) - 2\alpha\rho^2(m_f + p_s)}{2\alpha\nu(4\alpha - \gamma^2) - 2\alpha\rho^2} \tag{31}$$

$$e_f = \frac{\rho\overline{\overline{Q}} - 2\alpha\rho(m_f + p_s)}{\nu(4\alpha - \gamma^2) - \rho^2} \tag{32}$$

Then, Equations (31) and (32) are added to the profit function of the most upstream raw material manufacturer, namely, Equation (2), as follows:

$$\begin{aligned}\Pi_s = &\frac{\alpha\nu(\hat{Q} - \lambda(c_{s0} - c_s) + \rho e_{f0}) - \alpha^2\nu m_r}{\nu(4\alpha - \gamma^2) - \rho^2} \\ &- \frac{\alpha^2\nu(m_f + p_s)}{\nu(4\alpha - \gamma^2) - \rho^2}(p_s - m_s - w_s) \\ &- \tau\frac{\alpha\nu(\hat{Q} - \lambda(c_{s0} - c_s) + \rho e_{f0}) - \alpha^2 m_r\nu}{\nu(4\alpha - \gamma^2) - \rho^2} \\ &- \frac{\alpha^2\nu(m_f + p_s)}{\nu(4\alpha - \gamma^2) - \rho^2}(c_{s0} - c_s) - \frac{1}{2}\mu {c_s}^2\end{aligned} \tag{33}$$

$$\begin{aligned}\Pi_s = &\frac{\alpha\nu\hat{Q} - \alpha\nu\lambda(c_{s0} - c_s) + \alpha\nu\rho e_{f0}}{\nu(4\alpha - \gamma^2) - \rho^2} \\ &- \frac{\alpha^2\nu(m_f + p_s + m_r)}{\nu(4\alpha - \gamma^2) - \rho^2}(p_s - m_s - w_s) \\ &- \tau\frac{\alpha\nu\hat{Q} - \alpha\nu\lambda(c_{s0} - c_s) + \alpha\nu\rho e_{f0}}{\nu(4\alpha - \gamma^2) - \rho^2} \\ &- \frac{\alpha^2\nu(m_f + p_s + m_r)}{\nu(4\alpha - \gamma^2) - \rho^2}(c_{s0} - c_s) - \frac{1}{2}\mu {c_s}^2\end{aligned} \tag{34}$$

Based on Equation (34), it is time to calculate the best strategies for the raw material manufacturer.

The first-order, second-order, and joint partial derivatives of the variables in Equation (34) for the raw material manufacturer are listed as follows:

$$\frac{\partial \Pi_s}{\partial p_s} = \frac{\alpha\nu(\hat{Q} - \lambda(c_{s0} - c_s) + \rho e_{f0}) - \alpha^2\nu(m_f + m_r + p_s)}{\nu(4\alpha - \gamma^2) - \rho^2} - \frac{\alpha^2\nu}{\nu(4\alpha - \gamma^2) - \rho^2} + \frac{\tau(c_{s0} - c_s)\alpha^2\nu}{\nu(4\alpha - \gamma^2) - \rho^2} \tag{35}$$

$$\frac{\partial^2 \Pi_s}{\partial {p_s}^2} = \frac{-\alpha^2\nu}{\nu(4\alpha - \gamma^2) - \rho^2} \tag{36}$$

$$\frac{\partial \Pi_s}{\partial c_s} = \frac{\alpha\nu\lambda(p_s - m_s - w_s)}{\nu(4\alpha - \gamma^2) - \rho^2}$$

$$+\tau\frac{\alpha\nu(\hat{Q}-\lambda(c_{s0}-c_s)+\rho e_{f0})}{\nu(4\alpha-\gamma^2)-\rho^2}$$
$$-\tau\frac{\alpha^2\nu(m_f+m_r+p_s)}{\nu(4\alpha-\gamma^2)-\rho^2}$$
$$-\tau\frac{\alpha\nu\lambda}{\nu(4\alpha-\gamma^2)-\rho^2}(c_{s0}-c_s)-\mu c_s \tag{37}$$
$$\frac{\partial^2\Pi_s}{\partial {c_s}^2}=\frac{2\tau\alpha\nu\lambda}{\nu(4\alpha-\gamma^2)-\rho^2}-\mu \tag{38}$$
$$\frac{\partial^2\Pi_s}{\partial p_s c_s}=\frac{\partial^2\Pi_s}{\partial c_s p_s}=\frac{\alpha\nu\lambda-\tau\alpha^2\nu}{\nu(4\alpha-\gamma^2)-\rho^2} \tag{39}$$

Thus far, the extreme condition of the profit function of the available raw material manufacturer is

$$H=\frac{-\alpha^2}{(4\alpha-\gamma^2)-\frac{\rho^2}{\nu}}\left(\frac{2\tau\alpha\lambda-\mu((4\alpha-\gamma^2)-\frac{\rho^2}{\nu})}{(4\alpha-\gamma^2)-\frac{\rho^2}{\nu}}\right)-\left(\frac{\alpha\lambda-\tau\alpha^2}{(4\alpha-\gamma^2)-\frac{\rho^2}{\nu}}\right)^2>0 \tag{40}$$

After simplifying Equation (40), we obtain

$$\mu>\frac{2\lambda\tau\alpha}{(4\alpha-\gamma^2)-\frac{\rho^2}{\nu}} \tag{41}$$

Let Equations (35) and (37) equal 0, and combine them into simultaneous equations. In addition, let

$$Q^\#=\hat{Q}+\rho e_{f0}-\lambda c s_0-\alpha(m_f+m_r) \tag{42}$$

Solving the equation system, the best countermeasures for the raw material manufacturer can be obtained as (43) and (44), shown at the bottom of the page.

Equations (43) and (44) are added back to Equations (31) and (32) and then Equations (19) and (20), and the best response countermeasures for all supply chain members can be obtained.

Given the complex expressions of these strategies, they are not listed here. Next, numerical simulation is used to simulate the sensitivity of these exogenous variables to the key system parameters of the supply chain.

IV. NUMERICAL SIMULATION AND RESULT ANALYSIS

With the help of numerical simulation, the changing relationship between the supply chain performance index and key parameters can be described clearly. Because all parameters are dimensionless, their value range is relatively more flexible. In the theoretical model proposed in this study, because there are many variables and parameters, it is impossible to perform a one-to-one numerical simulation. This research is mainly aimed at green technology innovation in the supply chain under a carbon tax. Therefore, we select the carbon tax rate τ, the carbon footprint sensitivity coefficient of consumer demand λ, and the product energy efficiency sensitivity coefficient of consumer demand ρ as the key parameters of the supply chain system. Then, all exogenous variables are selected, that is, the variables that can explain the performance level of the system, including Q, p_r, π_s, π_f, π_r, π, c, and e.

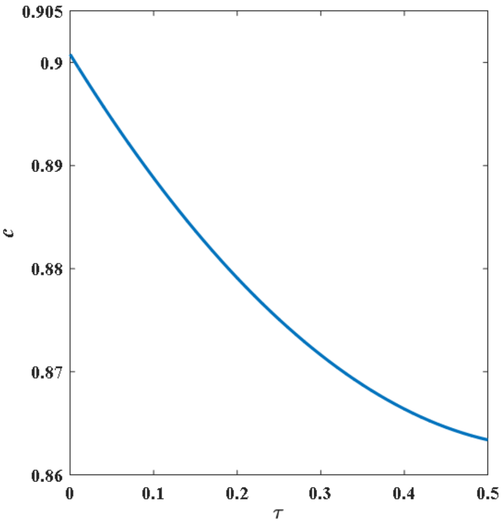

FIGURE 2. Relation between τ and c.

The numerical simulation first assigns initial values to the parameters. Iteratively, the three Hessian matrix conditions are verified in the game equilibrium analysis process until they are all satisfied. Then, the results are numerically simulated and plotted.

Expressly in this example, we set the following initial values for the parameters: $w_s=0.5$, $m_s=1$, $m_f=2$, $m_r=1$, $c_{s0}=1$, $e_{f0}=10$, $\nu=200$, $\tau=0.25$, $\alpha=50$, $\gamma=10$, $\lambda=10$, $\rho=30$, and $\hat{Q}=100$.

First, we evaluate the impact of carbon tax rates on the carbon emissions and profits of the raw material manufacturer, the profits of other supply chain members, and the overall supply chain profits, as shown in Figs. 2 and 3 below, respectively.

Second, our changes in the product carbon footprint, energy efficiency level, sales volume, and profits of all

$$p_s=\lambda\left(\frac{\nu\lambda(-\alpha+Q^\#-m_s-w_s)-\tau\alpha\nu(-\alpha+\alpha\tau c_{s0})}{\mu(\nu(4\alpha-\gamma^2)-\rho^2)-\nu\lambda^2-\tau^2\alpha^2\nu}\right)/\alpha-1$$
$$+\tau\left(c_{s0}-\frac{\nu\lambda(-\alpha+Q^\#-m_s-w_s)-\tau\alpha\nu(-\alpha+\alpha\tau c_{s0})}{\mu(\nu(4\alpha-\gamma^2)-\rho^2)-\nu\lambda^2-\tau^2\alpha^2\nu}\right)+\frac{Q^\#}{\alpha} \tag{43}$$
$$c_s=\frac{\nu\lambda(-\alpha+Q^\#-m_s-w_s)-\tau\alpha\nu(-\alpha+\alpha\tau c_{s0})}{\mu(\nu(4\alpha-\gamma^2)-\rho^2)-\nu\lambda^2-\tau^2\alpha^2\nu} \tag{44}$$

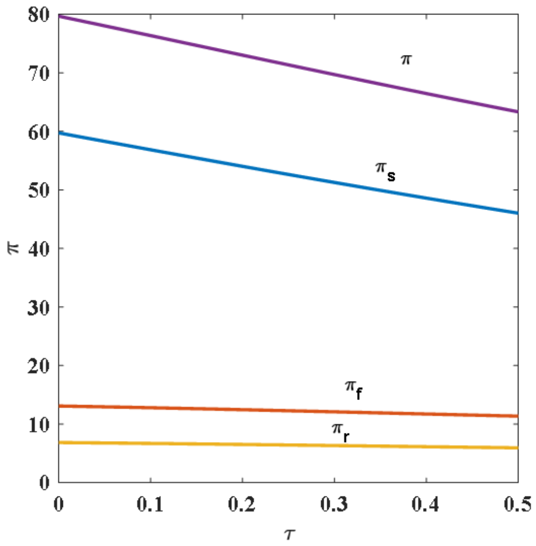

FIGURE 3. Relation between τ and π.

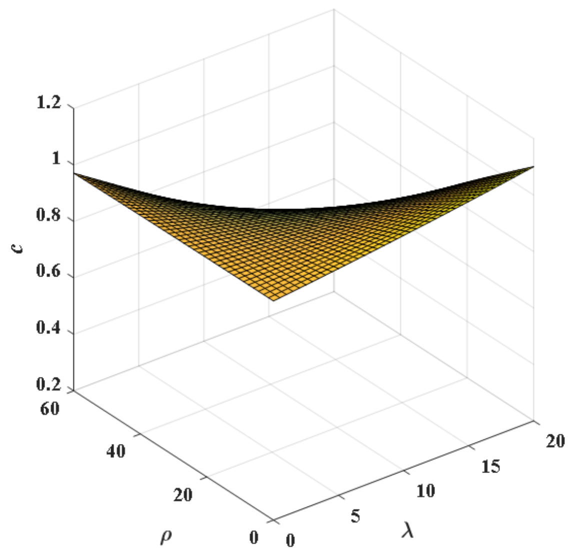

FIGURE 4. Relation between (ρ, λ) and c.

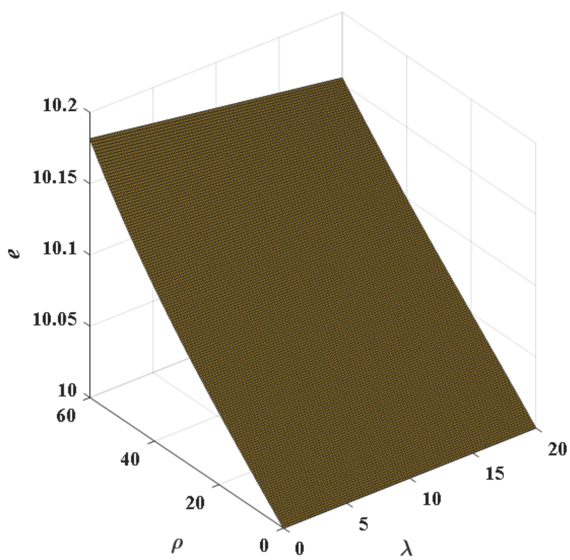

FIGURE 5. Relation between (ρ, λ) and e.

parties as the demand carbon footprint elasticity ρ and demand energy efficiency elasticity λ change are shown in Figures 4 to 7. Through this three-dimensional graph, the performance changes in the system can be observed when there are different changes in the parameters.

As shown in Fig. 2, with the gradual increase in the carbon tax rate, raw material processing enterprises have increased their efforts toward green technology innovation, and the carbon footprint of products has gradually decreased. However, the absolute value of the slope of the upward concave curve has also decreased, which means that the marginal emission reduction effect of the emission reduction policy is decreasing. When the carbon tax rate reaches 0.5, the carbon footprint of the product hardly decreases. The most significant social benefit of the policy is reflected in the fact that when the carbon tax rate increases from 0 to 0.01, the carbon footprint drops by 10% compared to that previously. As shown in Fig. 3, for supply chain member companies, under the carbon tax system, the carbon tax can only become a cost. In particular, with the increase in carbon tax rates, the profits of upstream raw material processing companies have been severely eroded, and it is difficult to transfer them all downstream. The profits of downstream final product manufacturers and retailers have little impact, and the overall profits of the supply chain have also shown a downward trend. The above factors are not conducive to the long-term sustainable development of the supply chain.

As shown in Fig. 4, as consumer demand becomes increasingly sensitive to the product carbon footprint and energy efficiency level, the product carbon footprint continues to decline, and the higher the demand sensitivity is, the faster the product carbon footprint changes. Similar to a black hole, the carbon footprint rapidly approaches zero. As seen from Fig. 5, the energy efficiency level of a product, or the green technology innovation level of the final product manufacturer, has an almost linearly increasing relationship with the elasticity coefficient of the energy efficiency of demand but decreases slowly with the increase in the elasticity coefficient of the carbon footprint of demand; alternatively, there may be few relations between them. On the whole, the energy efficiency level of the product continues to improve with the simultaneous increase in the two elastic coefficients.

It can be seen from Fig. 6 that the demand for products is positively correlated with the elastic coefficient of the energy efficiency of demand and also increases with the increase in the latter, and the growth rate exhibits an increasing trend. When the elastic coefficient of the demand carbon footprint is low, the correlation is more obvious. When the elasticity coefficient of demand is high, the demand for the product first decreases and then increases, which is a very exciting phenomenon. However, the relationship between demand and the demand carbon footprint elasticity coefficient is uncertain.

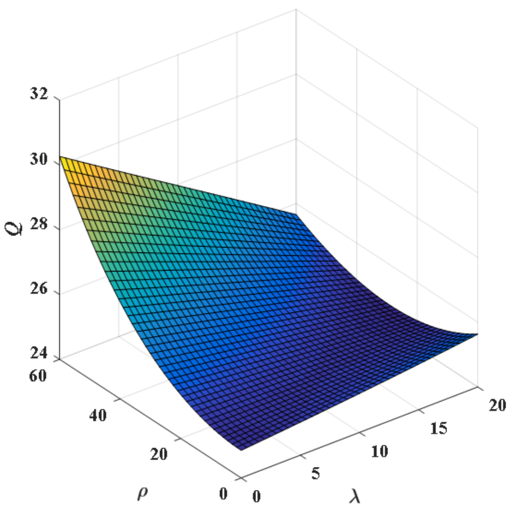

FIGURE 6. Relation between (ρ, λ) and Q.

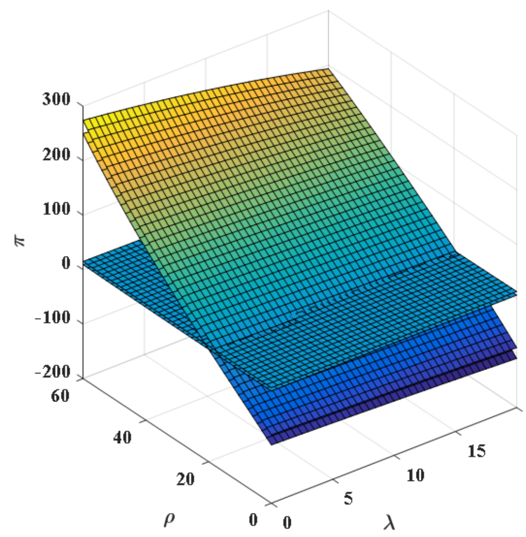

FIGURE 7. Relation between (ρ, λ) and π.

When the demand energy efficiency elasticity coefficient is low, the demand quantity increases with the demand carbon footprint elasticity coefficient. When the demand energy efficiency elasticity coefficient is high, the demand quantity decreases as the demand carbon footprint elasticity coefficient increases. As shown in Fig. 7, the overall profits of the raw material manufacturer and supply chains decrease with the increase in the elasticity coefficient of the demand carbon footprint but increase with the increase in the elasticity coefficient of the demand energy efficiency. For downstream final product manufacturers and retailers, the profit of the company slowly increases with the elasticity coefficient of the carbon footprint of demand, which has little or no relationship with the elasticity coefficient of energy efficiency of demand, or increases slightly.

Thus far, we have not only obtained the game strategy equilibria of stakeholders in the supply chain but also carried out sensitivity analysis on several key parameters in the system. Before reaching the conclusions of this study, we make necessary comparisons between the models, analysis or solution process and results of this study, and the 13 similar studies mentioned in Section I. The comparisons are mainly carried out from 5 aspects, including the network structure of the supply chain, carbon regulations, methodology used in model formulation and analysis procedure, whether sensitivity analysis or a numerical test is carried out, and the main research results. The first 4 aspects of each paper are listed in Table 2.

As seen from Table 2, the research object of supply chain green technology innovation has been limited to a single firm, such as in [12], [20], [28], and [29]; between upstream and downstream enterprises in the supply chain, including one supplier and one manufacturer, such as in [21], [24], and [27]; or between one manufacturer and one retailer, such as in [18], [19], [22], [23], and [25]. Reference [26] also studied a two-level supply chain with two competing downstream retailers. This paper has built a more complete, more complex, and more practical three-level supply chain. As mentioned in the conclusions in [21], [24], and [28], the study of a more complex supply chain structure is an inevitable direction of supply chain research at present and in the future.

As mentioned above, the carbon tax is a widely recognized and market-oriented carbon emission reduction mechanism. References [12], [20], [26] also studied supply chain carbon emission reduction under the carbon tax mechanism.

According to [12], the total carbon trading mechanism and carbon tax policy represent the future development direction of carbon emission reduction policies, which are more effective than are other carbon emission reduction policy mixes. In [12] and [20], it was said that the carbon tax was simpler than the carbon cap-and-trade mechanism. With the growth of the carbon tax, carbon emission costs promote continuous emission reduction, and the government also has an additional source of fiscal revenue. However, the limitations of the carbon tax were also analyzed in [20], and [26]. The carbon tax only increases the cost of the supply chain; it is a punishment mechanism but lacks an incentive mechanism. The carbon cap-and-trade mechanism is more perfect than is the carbon tax mechanism, but its design and implementation are also more complex. The allocation of carbon quotas is also a social problem that is difficult to balance. Regarding the research methods used in the literature, it can be seen in Table 2 that the research on the operation strategies of a single enterprise in the supply chain, including in [12], [20], [28], and [29], does not involve strategic interactions between stakeholders in the supply chain and generally uses traditional optimization technology, including mathematical programming models, accurate solution technology or intelligent algorithms, to solve the models. Except for these 4 articles, all other articles involve strategic interactions between at least two upstream and downstream enterprises in the supply chain. Although the strategies to be decided on may be different, they all need to be studied with the help of game theory.

TABLE 2. Research comparisons with existing literature.

Reference	Supply chain network structure	Carbon regulation	Methodology	Numerical experiment
[12]	A single firm	Carbon tax, carbon caps, cap and trade, carbon offsets	Mixed-integer programming	Yes
[18]	Dual level with one manufacturer and one retailer	Not stated	Differential game theory, supply chain contract design	Yes
[19]	Dual level with one manufacturer and one retailer	Not stated	Supply chain contract design	Yes
[20]	A single firm	Carbon tax, carbon tariff incentive, carbon tariff incentive forex	Multi-objective mixed-integer programming	Yes
[21]	Dual level with one supplier and one manufacturer	Cap and trade	Differential game	Yes
[22]	Dual level with one manufacturer and one retailer	Cap and trade	Supply chain contract design	Yes
[23]	Dual level with one manufacturer and one retailer	Green subsidy	Game theory	Yes
[24]	Dual level with one supplier and one manufacturer	Green credit financing with a carbon cap	Game theory	Yes
[25]	Dual level with one manufacturer and one retailer	Cap and trade	Game theory	Yes
[26]	Dual level with one supplier and two retailers in different channels	Carbon tax	Supply chain contract design	Yes
[27]	Dual level with one brand side and one manufacturer	Carbon intensity cap and trade	Game theory	Yes
[28]	A single firm	Not stated	Bi-objective mixed-integer programming	Yes
[29]	A single firm	Not stated	Bi-objective mixed-integer programming	Yes

The same is true for this paper. For example, [18], [19], [22], [26] used the theory of supply chain contracts, which, in fact, is also a branch of game theory, and its modeling and solving process are almost the same.

In terms of the research results, this paper finds that with the growth of the carbon tax rate, the supply chain cost gradually increases, which is consistent with the research results of [26]. However, as claimed in [12], the cost increases linearly in strict accordance with the fixed proportion of the carbon tax rate. This paper does not pay special attention to the changes in the cost of raw material manufacturers. In addition, both this paper and [12] find that when a carbon tax is first imposed, the amount of the emission reduction of enterprises or supply chains is the largest. With the continuous increase in the carbon tax rate, when it reaches a certain level, the emission reduction of enterprises or supply chains almost ceases because the cost of emission reduction is increasing. When the marginal cost of emission reduction exceeds the carbon tax rate, it becomes unfavorable in terms of reducing emissions. The profits of enterprises and supply chains subsequently decline. Therefore, when adopting the carbon tax rate policy to reduce emissions, it should always remain in moderation. In addition, as mentioned in the conclusions of this paper, [20] also believed that the carbon tax is purely an additional cost and burden for enterprises or supply chains and that a transfer payment mechanism can improve this defect of carbon tax policy and help enterprises achieve economic, environmental and social benefits at the same time. For some key parameters, this paper and [26] both pay attention to the elasticity coefficient of carbon emission reduction of market demand; [26] believed that the optimal amount of carbon emission reduction is positively linear with this coefficient. This paper also finds that they are positively but not nonlinearly correlated. This paper and [20] have found that the pricing strategy between different levels of supply chains has a great impact on the profits of supply chains, which is actually the so-called double marginal effect of supply chains. In [22] and [24]–[27], it is pointed out that the integration or centralized decision making of supply chains is very beneficial to the profits and emission reduction of the supply chain. However, in reality, this alliance is difficult to achieve, and the double marginal effect can only be reduced, not eliminated. Therefore, this study only considers the sequential game in the case of unequal bargaining power among supply chain members. Finally, in the numerical experiments, the highlighted key parameters for the sensitivity analysis are different. Some studies, such as references [12] and [26], have carried out sensitivity analysis for parameters separately, rather than parameter combinations, such as in [23] and [27] as in this paper. Furthermore, this paper uses a more compact combined parameter space, and the sensitivity analysis graph is smoother than those in other literature, but the effects are consistent.

V. CONCLUSION AND MANAGERIAL INSIGHTS

Taking the automobile, computer, communication or consumer electronics supply chain as the prototype, a three-level supply chain green technology innovation model including a raw material manufacturer, a final product fabricator, a retailer, and an end user is constructed. By applying the backward-induction analysis method, the best countermeasures and system performance indicators of all parties in the supply chain are obtained through analysis. With the help of numerical analysis, a series of performance indicators of the system and the response to the critical parameters of the system are analyzed intuitively and graphically. The main conclusions are presented below.

(i) Under carbon tax regulation, the profit for any member of the supply chain or the overall profit of the supply chain declines differently. Among them, the profit of the raw material manufacturer decreases most dramatically. The profit of the final product manufacturer and retailer also decrease but to a very limited extent due to the decline in the overall profit of the supply chain and the transmission of carbon tax costs of the raw material manufacturer to the downstream of the supply chain. This finding shows that as a one-way policy, when a carbon tax is adopted alone, it can only increase the cost of the supply chain, which is not conducive to the supply chain participating in international competition. Moreover, supply chain members cannot benefit from their green technology innovation activities. Therefore, we suggest that when implementing the carbon tax policy, the carbon tax should be used as a means of transfer payment to encourage firms to make more green technology innovation efforts and accelerate the elimination of enterprises with poor environmental performance.

(ii) Carbon tax regulation can encourage enterprises to actively carry out green technology innovation, but its marginal effect continues to decline. At the initial stage of carbon tax implementation, its impact on the level of green innovation efforts of enterprises is very obvious. Enterprises reduce carbon emissions through active green technology innovation and then reduce the additional costs brought about by the carbon tax. However, as the carbon tax increases to a certain level, the marginal emission reduction cost of firms gradually exceeds the carbon tax rate. At that moment, firms stop their green innovation efforts. To this end, we suggest that the initial carbon tax rate should be set at a low level and steadily increased in the future to allow time for firms to carry out green technology innovation and accumulate the funds and technologies required for continuous green innovation. We should be fully aware of the limitations of the carbon tax as a tool for emission reduction, not the higher, the better.

(iii) The carbon footprint elasticity and energy efficiency elasticity of consumer demand have a great impact on supply chain profit and carbon emission reduction. With demand becoming increasingly sensitive to the carbon footprint and energy efficiency level of products, the sales volume of the supply chain and its profit also increase quickly, while the carbon emission level decreases rapidly in the same period. In particular, it is found that the correlation intensity between consumer demand and product energy efficiency is significantly higher than that between demand and the product carbon footprint. Therefore, cultivating consumers' awareness and habits of green consumption is very important for the promotion of green technology innovation and enhancement of firm competitiveness. In addition, green consumers pay attention to the carbon footprint and energy efficiency level of products at the same time. The energy efficiency level, in fact, is the carbon footprint of products in the use phase. Its role in promoting the sales of green products is significantly greater than that of products in the production phase, which is also a reflection of consumers' rationality. From the perspective of regulators, we should create a competitive atmosphere that is conducive to improving the energy efficiency level of products rather than just emphasizing the carbon footprint of products. At the micro level, for the most upstream raw material manufacturer, also with the most power in the supply chain, its downstream enterprises should be urged to pay more attention to the efforts to enhance the energy efficiency level, or it should seek the final product manufacturers who are very good at the product energy efficiency level to form a more competitive green supply chain.

This study also has some limitations. First, a potential assumption of this paper is that between any two adjacent stakeholders in the supply chain, the upstream firm has greater bargaining power than does the downstream firm. People can study the situation in which the end product fabricator or retailer is dominant in the supply chain. Second, in this study, strategic interactions among supply chain members are carried out under the condition of complete information. Then, the supply chain green technology innovation game with asymmetric information and incomplete information may produce some very interesting results. Third, this paper only considers carbon tax regulation. The carbon cap-and-trade system, or the carbon tax policy considering the transfer payment mechanism, that is, providing financial compensation for leading green technology innovation enterprises, can be further studied in the future. We will leave the above issues to future researchers.

REFERENCES

[1] P. Friedlingstein *et al.*, "Global carbon budget 2021," *Earth Syst. Sci. Data*, vol. 14, no. 4, pp. 1917–2005, 2022, doi: 10.5194/essd-14-1917-2022.

[2] J. Xi, "Building on past achievements and launching a new journey for global climate action: Speech at climate ambition 2020," People's Daily, Dec. 14, 2020. [Online]. Available: http://paper.people.com.cn/rmrbhwb/html/2020-12/14/content_2023401.htm

[3] M. Z. Chishti, M. Ahmad, A. Rehman, and M. K. Khan, "Mitigations pathways towards sustainable development: Assessing the influence of fiscal and monetary policies on carbon emissions in BRICS economies," *J. Clean Prod.*, vol. 292, pp. 106273–106283, Apr. 2021, doi: 10.1016/j.jclepro.2021.126035.

[4] J. J. Andersson, "Carbon taxes and CO_2 emissions: Sweden as a case study," *Amer. Econ. J., Econ. Policy*, vol. 11, no. 4, pp. 1–30, Nov. 2019, doi: 10.1257/pol.20170144.

[5] A. B. Jaffe, R. G. Newell, and R. N. Stavins, "A tale of two market failures: Technology and environmental policy," *Ecol. Econ.*, vol. 54, nos. 2–3, pp. 164–174, Aug. 2005, doi: 10.1016/j.ecolecon.2004.12.027.

[6] G. Heal, "Discounting and climate change; an editorial comment," *Climatic Change*, vol. 37, no. 2, pp. 335–343, 1997, doi: 10.1023/A:1005384629724.

[7] C. A. McAusland and N. Najjar, "Carbon footprint taxes," *Environ. Resour. Econ.*, vol. 61, pp. 37–70, May 2015.

[8] I. Stepanov and K. Galimova, "Carbon price: Theory and practice of greenhouse gas emissions regulation," *Moscow Univ. Econ. Bull.*, no. 4, pp. 95–116, Aug. 2021, doi: 10.38050/01300105202165.

[9] J. Coria and J. Jaraite, "Carbon pricing: Transaction costs of emissions trading vs. carbon taxes," Feb. 2015, doi: 10.2139/ssrn.2573689.

[10] J. Guo, Y. Yang, and Z. Ma, "Constraint and incentive mechanism for business green technology innovation," *Sci. Technol. Manag. Res.*, vol. 20, pp. 249–252, Mar. 2018, doi: 10.3969/j.issn.1000-7695.2018.20.035.

[11] L. Wei and H. Zhang, "How environmental regulations affect the efficiency of green technology innovation?" *Amer. J. Ind. Bus. Manage.*, vol. 10, no. 3, pp. 507–521, Mar. 2020, doi: 10.4236/ajibm.2020.103034.
[12] S. Benjaafar, Y. Li, and M. Daskin, "Carbon footprint and the management of supply chains: Insights from simple models," *IEEE Trans. Autom. Sci. Eng.*, vol. 10, no. 1, pp. 99–116, Jan. 2013, doi: 10.1109/TASE.2012.2203304.
[13] R. Drozdenko, M. Jensen, and D. Coelho, "Pricing of green products: Premiums paid, consumer characteristics and incentives," *Int. J. Bus. Mark. Decis. Sci.*, vol. 4, pp. 106–116, Jan. 2011.
[14] Z. L. Liu, T. D. Anderson, and J. M. Cruz, "Consumer environmental awareness and competition in two-stage supply chains," *Eur. J. Oper. Res.*, vol. 218, no. 3, pp. 602–613, 2012, doi: 10.1016/j.ejor.2011.11.027.
[15] M. Meshkati, "The role of green marketing approaches in consumer behavior," *Singap. J. Bus. Econ. Manag.*, vol. 8, no. 3, pp. 122–132, 2021.
[16] W. Jiang, L. Yuan, L. Wu, and S. Guo, "Carbon emission reduction and profit distribution mechanism of construction supply chain with fairness concern and cap-and-trade," *PLoS One*, vol. 14, no. 10, 2019, Art. no. e0224153, doi: 10.1371/journal.pone.0224153.
[17] X. Li, D. Shi, Y. Li, and X. Zhen, "Impact of carbon regulations on the supply chain with carbon reduction effort," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 49, no. 6, pp. 1218–1227, Jun. 2019, doi: 10.1109/TSMC.2017.2741670.
[18] H. Yu, S. Bai, and D. Chen, "An optimal control model of the low-carbon supply chain: Joint emission reduction, pricing strategies, and new coordination contract design," *IEEE Access*, vol. 8, pp. 106273–106283, 2020, doi: 10.1109/ACCESS.2020.3000482.
[19] S. Swami and J. Shah, "Channel coordination in green supply chain management," *J. Oper. Res. Soc.*, vol. 64, pp. 336–351, Mar. 2013.
[20] L. K. Saxena, P. K. Jain, and A. K. Sharma, "A fuzzy goal programme with carbon tax policy for Brownfield Tyre remanufacturing strategic supply chain planning," *J. Cleaner Prod.*, vol. 198, pp. 737–753, Oct. 2018, doi: 10.1016/j.jclepro.2018.07.005.
[21] Y. Wang, X. Xu, and Q. Zhu, "Carbon emission reduction decisions of supply chain members under cap-and-trade regulations: A differential game analysis," *Comput. Ind. Eng.*, vol. 162, Dec. 2021, Art. no. 107711, doi: 10.1016/j.cie.2021.107711.
[22] Y. Cheng and P. Zhang, "Pricing strategy and coordination in an O2O mixed channel supply chain with carbon cap-and-trade mechanism," in *Proc. 36th Chin. Control Conf. (CCC)*, 2017, pp. 7528–7534, doi: 10.23919/ChiCC.2017.8028545.
[23] S. Yuan, J. Li, and X. Su, "Impact of government subsidy strategies on supply chains considering carbon emission reduction and marketing efforts," *Sustainability*, vol. 14, no. 5, p. 3111, 2022, doi: 10.3390/su14053111.
[24] S. An, B. Li, D. Song, and X. Chen, "Green credit financing versus trade credit financing in a supply chain with carbon emission limits," *Eur. J. Oper. Res.*, vol. 292, no. 1, pp. 125–142, Jul. 2021, doi: 10.1016/j.ejor.2020.10.025.
[25] U. Pathak, R. Kant, and R. Shankar, "Analytics of cap-and-trade policy for dual supply chain network structures," *Clean Technol. Environ. Policy*, vol. 22, no. 10, pp. 1999–2021, Dec. 2020, doi: 10.1007/s10098-020-01937-5.
[26] X. Zhu, L. Ding, Y. Guo, and H. Zhu, "Decisions and coordination of dual-channel supply chain considering retailers' bidirectional fairness concerns under carbon tax policy," *Math. Problems Eng.*, vol. 2022, pp. 1–15, Jan. 2022, doi: 10.1155/2022/4139224.
[27] J. Xie, J. Li, L. Liang, X. Fang, G. Yang, and L. Wei, "Contracting emissions reduction supply chain based on market low-carbon preference and carbon intensity constraint," *Asia-Pac. J. Oper. Res.*, vol. 37, no. 2, 2020, Art. no. 2050003, doi: 10.1142/S0217595920500037.
[28] M. Tavana, H. Tohidi, M. Alimohammadi, and R. Lesansalmasi, "A location-inventory-routing model for green supply chains with low-carbon emissions under uncertainty," *Environ. Sci. Pollut. Res. Int.*, vol. 28, no. 36, pp. 50636–50648, Sep. 2021, doi: 10.1007/s11356-021-13815-8.
[29] S. Mehrbakhsh and V. Ghezavati, "Mathematical modeling for green supply chain considering product recovery capacity and uncertainty for demand," *Environ. Sci. Pollut. Res. Int.*, vol. 27, no. 35, pp. 44378–44395, Dec. 2020, doi: 10.1007/s11356-020-10331-z.

JIDONG GUO was born in Jiaozuo, Henan, China, in 1977. He received the B.S. and M.S. degrees in engineering and the Ph.D. degree in management science and engineering from the Beijing University of Science and Technology, in 1999, 2006, and 2014, respectively.

From 2014 to 2020, he was a Lecturer in green supply chain management at the School of Economics and Management, Institute of Disaster Prevention. He has been an Associate Professor with the School of Emergency Management, since 2021. He is the author of a book and more than 20 articles. His research interests include low-carbon logistics, supply chain, low-carbon policy, green technology innovation, and supply chain emergency management.

MENGHAO XI was born in Yangquan, Shanxi, China, in 1967. He received the B.S. and M.S. degrees in engineering from Shanxi Normal University, in 1989 and 1995, respectively, and the Ph.D. degree in management science and engineering from the Beijing University of Aeronautics and Astronautics, in 2015.

From 2005 to 2011, he was an Assistant Professor in business administration at the School of Economics and Management, Institute of Disaster Prevention. He has been a Professor with the School of Emergency Management, since 2012. He is the author of three books and more than 30 articles. His research interests include decision-making technology, emergency logistics, and disaster risk assessment.