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Green Credit and Carbon Emission Reduction Technology R&D for Competitiveness

Junlong Chen, Hongzuo Shang, Pao Li, Jiali Liu

Abstract

Emission reduction technology R&D is an important way to promote the competitiveness of firms, and green credit plays an important role. Revealing the formation of green credit and carbon emission reduction technology R&D decisions and their mechanism is of great theoretical and practical significance for improving the green competitiveness of enterprises. Using the sequential game method, this study constructs a supply chain model consisting of one bank and two firms, analyzes the firms' green credit decisions and carbon emission reduction technology R&D decisions for competitiveness, considering R&D uncertainty, and expands the model by introducing environmental corporate social responsibility (ECSR) and nationalization. The results show that in Cournot competition, to ensure competitive advantage, only two cases can be subgame perfect Nash equilibrium (SPNE), and emission reduction technology R&D decisions are influenced by various factors, including carbon tax, deposit rate, and green credit management level. After the introduction of the ECSR, the total loan amount and equilibrium lending rate do not change, while under the nationalization policy, the total loan amount will decrease, and the lending rate will increase. These findings have theoretical significance for promoting carbon emission reduction technology R&D, optimizing green credit for banks, improving the green competitiveness of firms, and formulating effective industrial and financial policies for governments.

Keywords: *green credit, carbon emission reduction technology R&D, competitiveness, environmental corporate social responsibility, nationalization*

JEL Classification*: L13, M14, O11*

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1 INTRODUCTION

With the acceleration of climate change and the increasing global awareness of environmental challenges, sustainable finance has become an important policy tool for mitigating environmental damage and promoting sustainable economic growth. Green finance, particularly green credit, has emerged as a pivotal tool to promote eco-friendly investments and advance low-carbon technologies across industries (Narayan et al., 2022; Song et al., 2021). Considering China as an example, with the policy guidance that the Chinese government attaches great importance to environmental protection and sustainable development, green loans have emerged rapidly in China. By the end of the third quarter of 2023, the balance of green loans in China amounted to 28.58 trillion yuan, up 36.8% year-on-year, underscoring the critical role of financial mechanisms in supporting sustainable development and carbon neutrality (Arcuri & Pisani, 2021; Lian et al., 2022). Moreover, emission reduction technology R&D plays a crucial role in facilitating emission reduction efforts (Sun et al., 2024). In the context of developing a low-carbon economy, emission reduction technology R&D has become an important dimension for measuring the competitiveness of green development. Given the substantial costs, extended timelines, and inherent uncertainties associated with carbon reduction technology R&D, examining how green credit affects these efforts has gained increasing attention from both academia and industry. This study focuses on the following questions. As a credit system dedicated to promoting emission reduction (Sun & Zeng, 2023), what is the impact of green credit on carbon emission abatement technology R&D under uncertainty? What is the impact of green credit on the competitiveness of firms? What measures can be taken to promote green credit to give full play?

Despite the progress in green finance, there remains room for research on how green credit influences R&D decisions in competitive environments, particularly within supply chains comprising multiple entities. This study addresses this gap by constructing a sequential game model involving a bank and two competing firms to explore the strategic decisions surrounding green credit allocation and carbon emission reduction technology R&D. Unlike previous studies, our model incorporates environmental corporate social responsibility (ECSR) and nationalization policies to examine their effects on green credit utilization and innovation incentives (Francis et al., 2018; Kirimi et al., 2022). These findings provide crucial insights into optimizing green credit mechanisms, promoting sustainable corporate practices, and informing policy-making in green finance.

The main contributions of this study are as follows: First, it introduces a novel supply chain perspective by constructing a supply chain model of green credit and carbon reduction technology R&D that includes a bank and two firms, which compensates for the current literature that examines green credit and carbon reduction technology R&D simultaneously to improve the competitiveness of the supply chain (Li et al., 2023). Second, this study provides insights into the impact of uncertainty on R&D success and competitiveness, thus expanding the area of limited attention in the related literature (Xing et al., 2021; Zhang et al., 2023). Finally, by examining the roles of ECSR and nationalization, this study sheds light on how regulatory frameworks and corporate responsibilities shape sustainable finance practices and their alignment with environmental goals (Gao & Liu, 2023).

Thus, this study contributes a comprehensive framework for understanding and leveraging green credit to foster carbon reduction technology R&D. This study constructs a four-stage sequential game model of the bank and two firms, obtains the equilibrium output and equilibrium carbon emission reduction of the two firms, as well as the loan amount and equilibrium loan interest rate decided by the bank. This study finds that a firm's decision of emission reduction R&D is affected by the probability of success of R&D, carbon tax, deposit interest rate, and the level of green credit management and other factors, and there are only two sub-games of neither R&D and both R&D perfect Nash equilibrium. In addition, the research problem is expanded by introducing the factors of ECSR and the level of nationalization, and through equilibrium and comparative analysis, it is found that environmentally friendly corporate social responsibility only affects the loan volume of each of the two firms. Whereas, the nationalization of the bank not only affects the loan volume of a single firm but also reduces the total loan volume and increases the equilibrium loan interest rate decided by the bank.

The remainder of the paper is organized as follows. Section 2 presents a supply chain model considering green credit and R&D of emission reduction technology for competitiveness. Section 3 analyzes the different scenarios of R&D decisions and outcomes individually, derives the equilibrium results for each scenario, and explores the impacts of various parameters. Section 4 deals with the extension of the model and examines the impact of incorporating the ESCR and nationalization on green credit. Section 5 presents the discussion of the results and finally. Section 6 concludes the paper.

2 THEORETICAL BACKGROUND

R&D is an effective way to improve the technological capabilities of firms, promote economic growth, and significantly improve the global competitiveness of countries (Kiselakova et al. 2018; Jin et al., 2024). The R&D of carbon emission reduction technology not only enhances the market competitiveness of firms but also plays a significant role in promoting environmental protection, social welfare, and sustainable economic development (Chen et al., 2023a). The conceptual model in this study examines how green credit affects emission reduction technology R&D within a competitive supply chain setting involving one bank and two firms. Green credit helps to provide financial support for eco-friendly R&D projects, which is crucial for high-emission industries (Ding et al., 2022), and an effective green credit policy not only improves firms' green productivity but also reduces non-performing loans associated with eco-friendly projects, which enhances banks' financial stability (Cui et al., 2018). Recent research highlights how green credit improves firms' environmental and social governance (ESG) and provides insights into policy applications (Wang et al., 2023; Hameed et al., 2023). The extant literature provides a good theoretical basis for this study. Based on the existing research, this study conducts further research on the literature in combination with green credit.

2.1 Green credit

The literature on green credit is relatively rich and mostly links it to financing constraints, financial performance, and green innovation. Several studies emphasize the impact of green credit on banks' credit risk and profitability. Ding et al. (2022) argued that green credit significantly contributes to the sustainable development of banks, and Cui et al. (2018) showed that green lending reduces banks' non-performing loan ratio, which has a positive impact on both credit risk and financial performance. Additionally, numerous studies have shown that green credit promotes green technological innovation and reduces carbon emissions. Lv et al. (2023) found that green credit can affect the green productivity of firms through financing scale and cost effects, which provides useful insights for the government to further standardize the green credit system and ensure the effective implementation of green credit policies. Xi et al. (2022) analyzed the development dynamics and value creation of green credit and the mechanism by which green credit improves the financial performance of listed banks. Hu et al. (2023) explored the impacts of the green credit policy on different types of green innovations and found that green credit increased low-quality green innovations but not high-quality innovations. Su et al. (2022) examined the nonlinear impact of green credit on green technological innovation and found that if green credit is below a threshold, green technological innovation is inhibited, and the disclosure of environmental information plays a key role. Green credit policies significantly influence firms' strategies in competitive markets. Chen et al. (2023b) demonstrated that oligopolistic firms benefit from green credit policies because they improve green innovation performance and competitive positioning. Xu et al. (2023) found that green credit can effectively reduce the intensity of carbon emissions; specifically, green credit primarily reduces carbon intensity by reducing investment in green innovation. Yu et al. (2022) argued that green credit must be accompanied by the implementation of related policies to promote green innovation in firms. Based on empirical research conducted in China (Gao & Liu, 2023) and globally (Al Mamun et al., 2022), green credit significantly reduces carbon emissions and improves the firms' environmental performance. These studies provide useful theoretical support and insights for this study to analyze the impact of green credit on the R&D of emission reduction technologies under uncertainty.

2.2 Carbon emission reduction technology R&D

The literature on carbon emission reduction technology R&D focuses on influencing factors, incentives, and decision strategies (Gonenc & Poleska, 2022; Liu et al., 2022). Existing studies have shown that R&D on emission reduction technologies is influenced by multiple internal and external factors, and incentive-compatible mechanisms should be designed to optimize firms' R&D decisions on emission reduction technologies, thereby promoting R&D activities on emission reduction technologies. Chen et al. (2024) suggested that firms' technology R&D decisions are influenced by technology spillovers, cost differences, and bargaining power. Yin and Chang (2020) concluded that the costs of the optimal policy to reduce carbon emissions are lower than those of R&D investment in energy efficiency and low-carbon technologies. Uncertainty has an important influence on firms' technological innovation behavior and is a crucial factor to be considered in the R&D process of carbon emission reduction technology. Bosetti and Tavoni (2009) analyzed the optimal investment in carbon emission reduction innovations in response to stringent climate targets and uncertainty regarding the effectiveness of R&D. Zhang and Liu (2023) posited that the R&D process can incur significant costs and inefficiencies owing to factors such as long lead times, outcome uncertainty, and insufficient historical data. Consequently, selecting an R&D portfolio is often a complex decision problem. According to the relevant literature on carbon emission reduction technology R&D, the influencing factors of carbon emission reduction technology R&D for competitiveness are complex and diverse, the mechanism design needs to be improved, and multiple subjects participate in the decision-making process, which provides the basis for the model design and analysis of this study.

3 OBJECTIVE AND METHODOLOGY

3.1 Objective

The main objectives of this study are as follows. First, it determines the green credit decision outcome and the conditions under which the two firms carry out carbon emission reduction technology R&D under Cournot competition, and second, it introduces ESCR and nationalization and determines the green credit outcomes and their influencing factors.

3.2 Methodology

To achieve these objectives, this study analyzes a multistage game of green credit and emission reduction technology development using sequential game theory. The sequential game is a form of game in which participants choose strategies in chronological order, and it is suitable for describing the complex game relationships of different subjects in multiple stages. Sequential games have been widely used by academics in renewable energy investment, healthcare pricing, capacity decision making, and supply chain management (He & Wang, 2023; Meng et al., 2023; Zhan et al., 2022). Green credit and firms' R&D decisions on emission reduction technologies are dynamic games at different stages, and sequential game theory can be used to explore the equilibrium between credit behavior and R&D decisions. Therefore, this study constructs a supply chain model involving a bank and two firms using the sequential game method. The theoretical framework of this study is illustrated in Fig. 1.

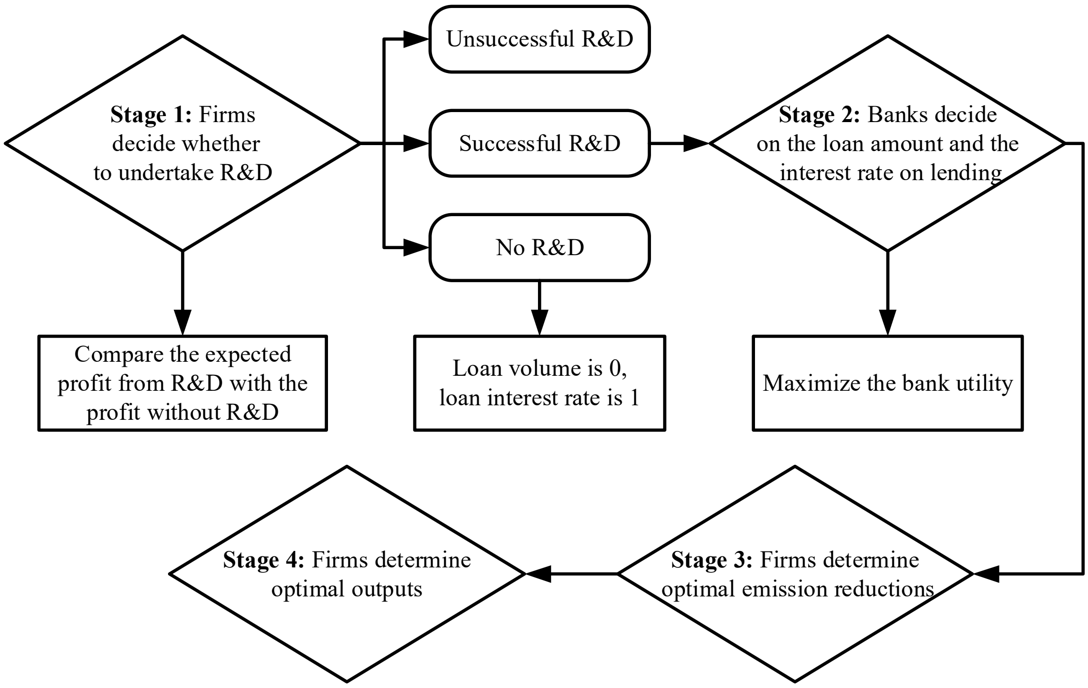

Fig. 1 – Theoretical framework. Source: own research

1. In the supply chain model, the upstream consists of a bank facing a decision to provide green credit to two downstream firms (Firms 1 and 2) for carbon emission reduction technology R&D. The bank faces a downward-sloping inverse demand function with a lending rate $r_L = 1 - (l_1 + l_2)$, where l_i represents the loan of Firm i ($i = 1{,}2$ and $i \neq j$), and its profit can be mathematically expressed as

$$\pi_B = [1 - (l_1 + l_2) - r_D](l_1 + l_2) - \frac{\varphi(l_1+l_2)}{2} \quad (1)$$

where r_D is the deposit rate, and $\frac{\varphi(l_1+l_2)}{2}$ is the operating and regulatory cost, where $0 \leq r_D \leq 1$, $0 < \varphi < 1$, which indicates green credit management. The level of green credit management increases as φ decreases. The implication of these assumptions is that banks must implement appropriate standardized procedures for granting loans and strengthen their management of loans to avoid credit risk. The operating and regulatory costs a bank pays for each loan depend on its green credit management level. This means that the larger the amount of credit, the higher the operating and regulatory costs that the bank must pay.

2. In the supply chain model, the downstream consists of two firms engaging in Cournot competition over output. The downstream firms' inverse demand function is $p = a - q_1 - q_2$, where $a > 0$. Both firms incur costs related to carbon emissions and carbon tax. For simplicity of analysis, it is assumed that there are no additional costs associated with production. The cost function for each firm, denoted by c_i, is given by the equation $c_i = \frac{\theta_i^2}{2} + te_i$ (Dong & BarcenaRuiz, 2021; Wang et al., 2019), where t is the carbon tax, e_i is the carbon emission, θ_i is the emission reduction, and there is $\theta_i = q_i - e_i$ (Buccella et al., 2021).

3. Downstream firms are faced with the decision of whether to engage in R&D activities related to carbon reduction technology. If Firm $i(i = 1{,}2, j = 3 - i)$ chooses not to conduct carbon emission reduction technology R&D, the firm's profit is

$$\pi_i^N = (a - q_i - q_j)q_i - c_i \quad (2)$$

If the Firm i pursues R&D in this area, it must seek a green loan from an upstream bank and pay a lending rate of r_L to obtain a loan of l_i for R&D. After conducting successful R&D, the $\frac{\theta_i^2}{2}$ cost becomes $\frac{l_i\theta_i^2}{2}$, Additionally, the profit function is modified

$$\pi_i^{RY} = (a - q_i - q_j)q_i - te_i - r_L l_i - \frac{l_i\theta_i^2}{2} \quad (3)$$

If R&D efforts are unsuccessful, the profit of Firm i can be represented as

$$\pi_i^{RN} = (a - q_i - q_j)q_i - c_i - r_L l_i \quad (4)$$

R&D is risky, assuming that the probability of success is $\mu(0 \leq \mu \leq 1)$, therefore, the expected profit is $E(\pi_i^R) = \mu\pi_i^{RY} + (1-\mu)\pi_i^{RN}$.

4. We set up a four-stage sequential game involving one bank and two firms. In the first stage, firms decide whether to conduct R&D on carbon emission reduction technology. The condition for Firm i to conduct R&D is that the expected profit from R&D is greater than or equal to the profit from not conducting R&D, that is, $E(\pi_i^R) \geq \pi_i^N$. In the second stage, the bank determines the optimal loan amount (l_i^*) and lending rate (r_L^*) for each firm, considering the goal of profit maximization. In the third stage, the two firms determine the optimal emission reductions based on the profit maximization objective. In the fourth stage, the two firms decide on optimal outputs. The meanings of the relevant notations are listed in Tab. 1.

Tab. 1 – The notations used in the models. Source: own research

Notations	Descriptions
r_L	lending rate
r_D	deposit rate
l_i	the loan of Firm i, $i = 1,2$
L	total loans
φ	the level of green credit management
c_i	cost function of Firm i
p	product price
q_i	output of Firm i
Q	total outputs
t	carbon tax rate
e_i	carbon emission of Firm i
θ_i	emission reduction of Firm i
μ	probability of R&D success
π_B	profit function of bank
π_i	profit function of Firm i
π_i^N	Profit function of Firm i without R&D
π_i^{RY}	Profit function of Firm i at R&D success
π_i^{RN}	Profit function of Firm i when R&D fails
u_B	utility function of bank
δ	nationalization level of bank
DE	damage to the environment
CS	consumer surplus
SW	social welfare

4 RESULTS

4.1 Results of model

Using the backward induction method, the optimal emission reduction and production decisions of the firms in the third and fourth stages are first examined. In the first stage, firms decide whether to engage in R&D activities. This decision leads to nine possible outcomes, considering the equilibrium levels of emission reductions and outputs under different cases.

Result 1-1: equilibrium levels of emission reductions and output under different cases are

$$q_i^{RY} = q_i^{RN} = q_i^N = \frac{a-t}{3} \tag{5}$$

$$\theta_i^{RY} = \frac{t}{l_i}, \theta_i^{RN} = \theta_i^N = t \tag{6}$$

As shown in Result 1-1, it is evident that the output of both firms is $\frac{a-t}{3}$. Simultaneously, Firm i remains unaffected by the other firms. When the firm succeeds in R&D, the equilibrium emission reduction is $\frac{t}{l_i}$ and when the firm is unsuccessful or chooses not to engage in R&D, the equilibrium emission reduction is t, that is, the profit generated by an individual firm is solely influenced by its own R&D decisions.

Examining the second stage of the bank' s decision-making process, it aims to maximize its own profit on the lending rate r_L, the loan of Firm 1 l_1 and the loan of Firm 2 l_2. At this point, the equilibrium lending rate $r_L^* = \frac{2+2r_D+\varphi}{4}$, the total loans made to the two firms is $L = \frac{2-2r_D-\varphi}{4}$, where $0 \leq 2r_D + \varphi \leq 2$. This shows that profit optimization can be achieved by reaching a specific threshold of total loans, regardless of the specific combination of loans allocated to the two firms. Specifically, when the level of regulation is higher, the lending rate also tends to be higher. Therefore, reducing regulatory costs through effective measures is an effective way for banks to enhance their competitiveness.

By analyzing the R&D decisions of the two firms in the first stage, Firm i conducts carbon emission reduction technology R&D if the condition $E(\pi_1^R) \geq E(\pi_1^N) = \pi_1^N$ is met, which can be described as

$$\mu \geq \frac{(2+2r_D+c){l_i}^2}{2t^2(1-l_i)} \tag{7}$$

Result 1-2: The effect of t, r_D and φ on the R&D decision boundary:

Let $T_i = \frac{(2+2r_D+c){l_i}^2}{2t^2(1-l_i)}$, we have $\frac{\partial T_i}{\partial t} < 0$, $\frac{\partial T_j}{\partial t} < 0$; $\frac{\partial T_i}{\partial r_D} > 0$, $\frac{\partial T_j}{\partial r_D} > 0$; $\frac{\partial T_i}{\partial \varphi} > 0$, and $\frac{\partial T_j}{\partial \varphi} > 0$.

As shown in Result 1-2, an increase in the carbon tax rate t favors carbon emission reduction technology R&D. When the carbon tax rate t increases, the critical values T_i and T_j both decrease, reducing the probability of R&D success required for firms to choose R&D. This creates a stronger economic incentive for firms to engage in R&D and pursue green innovation, as higher carbon taxes raise the cost of pollution and make emission-reducing technologies financially more attractive. Conversely, an increase in bank deposit rate r_D negatively impacts firms' motivation for emission reduction R&D. When the bank deposit rate r_D increases, the critical values T_i and T_j both increase accordingly, raising the probability of R&D success required for firms to choose R&D to a certain extent, inhibiting the R&D motivation of firms, and hindering their carbon emission reduction actions. The enhancement of the bank's green credit management level, which means c decreases, is favorable for firms' carbon emission reduction technology R&D. At this point, the critical values T_i and T_j decrease simultaneously, thereby diminishing the probability of R&D success, which is necessary for firms to opt for R&D. Consequently, it prompts the two firms to display a greater inclination toward undertaking R&D activities focused on carbon emission reduction technology for competitiveness.

Finally, the examination of the potential existence of subgame perfect Nash equilibrium (SPNE) is warranted. When $l_i \geq \frac{2-2r_D-\varphi}{8}$, $l_i \geq l_j$ and $T_i \geq T_j$, the success probability of the firm's R&D μ is discussed.

Result 1-3:

(1) $\mu < T_j$: Both Firm i and Firm j choose not to conduct R&D. At this time, $l_i = l_j = 0$, $L = \frac{2-2r_D-\varphi}{4} = 0$. Therefore, the only time when $r_L^* = 1$, that is $\varphi = 2 - 2r_D$, the equilibrium result is that neither of the firms conducts R&D.

(2) $T_j \leq \mu < T_i$: Firm i chooses not to conduct R&D, and Firm j chooses to do it. At this time, $l_i = 0$, $l_j = \frac{2-2r_D-\varphi}{4} > 0$, which does not meet the prerequisites $l_i \geq l_j$. Therefore, this situation does not occur.

(3) $\mu \geq T_i$: Firm i and Firm j both choose R&D. At this time, $l_i > l_j > 0$, $r_L < 1$, i.e., $\varphi < 2 - 2r_D$.

This leads to Result 1-4.

Result 1-4: Only two cases can be SPNE, viz. neither of the firms conducts R&D, and both firms conduct R&D.

Notably, at this point in the supply chain model, there is no situation in which one company performs R&D for competitiveness and the other does not. This outcome reflects the competitive dynamics within the supply chain model, in which investing in carbon emission reduction technology provides a significant competitive advantage. Consequently, when one firm opts to pursue R&D to enhance its market position, the other firm is economically incentivized to follow, thus preventing a loss in its relative competitiveness. This mutual commitment to innovation aligns with real-world scenarios in which firms in competitive markets often mirror each other's sustainability strategies to avoid being disadvantaged. Consequently, the model underscores the role of green R&D as both a strategic necessity and driver of industry-wide advancements in sustainable practices.

4.2 Model extension

Assuming that firms consider ECSR, which incorporates damage to the environment (DE) into the consideration of the bank' s decision, changing the bank utility function to $u_B = \pi_B - \beta DE$ ($0 \leq \beta \leq 1$), where $DE = \frac{(e_1+e_2)^2}{2} = \frac{(q_1+q_2-\theta_1-\theta_2)^2}{2}$, consists of the emissions of the two firms e_1 and e_2 are determined, that the greater the environmental damage, the smaller the bank's utility. At this juncture, an alteration in the bank's utility function solely impacts the bank's decision in the second-stage game and the firm's decision in the first stage.

Result 2-1: ECSR does not exert any influence on the equilibrium lending rate r_L^* and total loans L.

In the equilibrium results, only the loan of each of the two firms is different from that of the basic model, and except for the case where both of them choose not to conduct R&D, the equilibrium lending rate decided by the bank, regardless of the R&D results, is always $r_L^* = \frac{2+2r_D+\varphi}{4}$ and total loans are always $L = \frac{2-2r_D-\varphi}{4}$, consistent with the results of the bank's decision in the basic model. Therefore, the corresponding carbon finance policies must be continued. If an individual desires to adjust the lending capacity of a specific firm without affecting the social interest rate or overall lending capacity, ECSR can be considered. ECSR involves incorporating an assessment of environmental damage into a bank's decision-making process (Xing & Lee, 2024).

Reconsider the introduction of nationalization level δ $(0 \leq \delta \leq 1)$, the bank utility function becomes $u_B = (1-\delta)\pi_B + \delta SW$, where the social welfare is $SW = \pi_B + \pi_1 + \pi_2 + CS - DE$, containing the profits of the two firms π_1 and π_2, consumer surplus $CS = \frac{(q_1+q_2)^2}{2}$ and environmental damage $DE = \frac{(e_1+e_2)^2}{2} = \frac{(q_1+q_2-\theta_1-\theta_2)^2}{2}$.

In all scenarios, removing the fact that both firms choose not to conduct R&D, the total loans can be expressed as $L = \frac{2-2r_D-c-2\delta}{4(1-\delta)}$, and the equilibrium lending rate is given by $r_L^* = \frac{2+2r_D+c-2\delta}{4(1-\delta)}$. For a better comparison with the basic model, the variables ΔL and Δr_L^* are introduced:

$$\Delta L = L_N - B = -\frac{(\varphi+2r_D)\delta}{4(1-\delta)} \tag{8}$$

$$\Delta r_L^* = {r_L^*}_N - {r_L^*}_B = \frac{(\varphi+2r_D)\delta}{4(1-\delta)} \tag{9}$$

Based on the given conditions that $0 \leq \delta \leq 1$, $0 \leq r_D \leq 1$ and $0 < \varphi < 1$, it is easy to deduce that $\Delta L \leq 0$ and $\Delta r_L^* \geq 0$.

Result 2-2: the nationalization policy reduces total loans L and increases the equilibrium lending rate r_L^*.

Under the nationalization policy, banks consider various factors such as firms' profits, consumer surplus, and environmental damage in their decision-making process. When considering only the latter two factors, the bank does not alter the overall amount of loans and the equilibrium lending rate. However, when the factor of total corporate profits is considered, the bank is motivated to decrease the total loans L and increase the equilibrium lending rate r_L^* to improve total profits, thereby contributing to social welfare. Therefore, carbon financing policies should be adjusted accordingly. This outcome has practical implications: by prioritizing financial sustainability, nationalized banks can allocate green loans more selectively, ensuring that funds are allocated to projects with the highest environmental and social returns. For policymakers, this suggests that carbon finance policies should be adaptable to align with national goals, balancing profitability with environmental protection to maximize the social impact of green finance.

Result 2-3: The effect of δ, r_D and φ on the ΔL and Δr_L^*:

$\frac{\partial|\Delta L|}{\partial\delta} > 0$, $\frac{\partial|\Delta r_L^*|}{\partial\delta} > 0$; $\frac{\partial|\Delta L|}{\partial r_D} > 0$, $\frac{\partial|\Delta r_L^*|}{\partial r_D} > 0$; $\frac{\partial|\Delta L|}{\partial\varphi} > 0$, $\frac{\partial|\Delta r_L^*|}{\partial\varphi} > 0$.

From these results, the increase in δ, r_D, and c not only intensifies the inhibitory impacts of the nationalization policy on firms' green credit but also strengthens its enhancing effect on the equilibrium lending rate. Therefore, nationalization policies must be implemented in conjunction with the deposit rate and level of regulation.

5 DISCUSSION

The results of this study reveal the factors influencing R&D competition for green credit and carbon emission reduction technologies under different conditions. The conclusions of this study are as follows:

First, the emission reduction technology R&D decisions for the competitiveness of the two firms are influenced by factors such as carbon tax, deposit rates, level of green credit management, and success probability. Profit optimization can be achieved if a specific threshold for total loans is reached. The loan interest rate tends to increase when the regulatory level is higher. These findings suggest that an increase in the carbon tax rate and green credit management level encourages firms to invest in emission reduction R&D, which is consistent with prior studies that highlight these factors as key drivers of green innovation (Lv et al., 2023; Yin & Chang, 2020). However, increased deposit rates have an inhibitory effect on R&D, echoing the observations by Zhang and Liu (2023) that rising capital costs can dissuade R&D investments. This underscores the need for a balanced approach when formulating carbon finance policies to sustain firms' competitiveness and commitment to sustainability initiatives in emission reduction R&D.

Second, only two cases can be SPNE, viz. neither of the firms conducts R&D, and both firms conduct R&D. This outcome aligns with recent studies on R&D competition in duopolies, such as those by Xing et al. (2021), who suggest that firms in competitive markets tend to mirror each other's strategies in high-stakes R&D ventures to avoid competitive disadvantages. This observation contributes to the existing discourse on competitive behaviors under uncertain R&D outcomes, as explored by Gonenc and Poleska (2022).

Third, the implementation of ECSR and nationalization policies affects the equilibrium results. The influence of ECSR on loan allocation but not on equilibrium lending rates is consistent with the findings of Chen et al. (2023b), who describe ECSR as a non-monetary factor that primarily affects credit allocation decisions without altering the loan structure. Conversely, nationalization decreases total loans while increasing lending rates, a trend observed in Du and Guo (2023) in their analysis of green credit under public sector oversight. This suggests that nationalized banks may adopt more conservative lending practices that influence firms' access to green finance and, consequently, their R&D investment decisions.

The results of this study show that green credit has an important impact on corporate carbon reduction technology innovation and competition, which is consistent with the existing research (e.g., Chen et al., 2019; Mi et al., 2024). This study considers the R&D decisions of firms on carbon emission reduction technologies under green credit from the perspective of firm competition and introduces ESCR and nationalization for the analysis, which is an important contribution to the existing literature. This finding differs from that of Chen et al. (2023b), who believe that more socially responsible firms have stronger incentives to promote their environmental performance without considering bank decisions. Banks can optimize their lending strategies by integrating CSR and nationalization considerations, thereby aiding firms in reducing emissions and promoting sustainable R&D. Firms can strategically use green loans to support R&D efforts, particularly when regulatory pressures align with CSR policies. By understanding these dynamics, financial institutions can encourage green innovation and help firms overcome financial obstacles in emission reduction R&D.

Policymakers can leverage these insights to enhance green credit schemes by incorporating ECSR and nationalization adjustments. For instance, increasing the carbon tax rate and encouraging ECSR practices may further incentivize firms to invest in emission reduction R&D. Additionally, establishing government-backed green credit programs may reduce financing barriers for firms and improve their overall environmental performance. Tailored regulatory adjustments such as tax credits for green R&D and subsidies aligned with green credit programs can foster more effective green innovation strategies.

6 CONCLUSION AND FUTURE RESEARCH DIRECTIONS

6.1 Conclusion

This study offers a comprehensive analysis of how green credit influences firms' carbon emission reduction technology R&D within a competitive market setting by incorporating ECSR and nationalization factors. By constructing a sequential game model, this study uncovers two critical findings. First, the effectiveness of green credit policies in driving sustainable R&D efforts is highly contingent on the balance of carbon tax, deposit rates, and green credit management levels. Second, both ECSR and nationalization policies significantly shape firms' strategic responses to green credit, impacting loan allocations and lending rates.

These findings provide valuable insights for policymakers and industry stakeholders. For banks, optimizing green credit policies can encourage sustainable practices and support firms' green innovation, whereas government bodies may consider policy adjustments to strengthen green finance frameworks.

6.2 Limitations and Potential Areas of Future Study

This study has some limitations that should be addressed in future studies. First, this study only introduces a comparative analysis of the model with ESCR and nationalization, and we can add more factors for in-depth consideration. Second, this study does not consider Stackelberg and Bertrand models, and we can include more types of market competition. Third, this study assumes that there are only two competitors and one bank, and the analysis can be extended to more entities in the future. Fourth, this study employs an end-of-pipe treatment model ($\theta_i = q_i - e_i$) to assess emission reduction, which focuses on post-production pollutant management. However, this approach does not capture cleaner production technologies, where emission reductions are integrated directly into the production process (e.g., $\theta_i = (1 - e_i)q_i$). Future research should broaden this model to include cleaner production technologies and provide a more comprehensive view of the emission reduction strategies available to firms. Additionally, comparing the cost-effectiveness and adoption trends of end-of-pipe and cleaner production technologies can provide insights into firms' strategic responses to green finance incentives. By investigating these areas, future studies can offer valuable guidance to policymakers and industry leaders for promoting a balanced and effective approach to sustainable development.

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Contact information

Prof. Junlong Chen, Ph.D.
Northeastern University
School of Business Administration
Shenyang, China
Northeastern University at Qinhuangdao
School of Economics
Qinhuangdao, China
E-mail: shikuangzhiwang@126.com
ORCID: 0000-0001-8962-2567

Hongzuo Shang, Undergraduate
Jilin University
School of Economics
China
E-mail: shanghz0622@mails.jlu.edu.cn
ORCID: 0009-0003-5277-9239

Pao Li, Undergraduate
Northeastern University at Qinhuangdao
School of Economics
China
E-mail: 202110109@stu.neu.edu.cn
ORCID: 0009-0001-0066-3125

Prof. Jiali Liu, Ph.D. (Corresponding author)
Jilin University
Center for China Public Sector Economy Research
Changchun, China
Jilin University
School of Economics
Changchun, China
E-mail: liujiali@jlu.edu.cn
ORCID: 0000-0002-1168-3295