

Does carbon reduction label work? From a perspective of agricultural product supply chain with consumer's low-carbon preference and label recognition

Huan Zhang ^{1, a}, Shucui He ^{1, b}, and Jianli Jiang ^{2, c, *}

¹ Department of Economic Management, North China Electric Power University, Huadian Road, Baoding, 071100, Hebei, China;

² School of Business Administration, China University of Petroleum-Beijing at Karamay, Xinjiang, 834000, China.

^a huanzhang@ncepu.edu.cn, ^b 1301089945@qq.com, ^c 2024592121@cupk.edu.cn

Abstract. Agricultural product supply chain faces the twin challenges of carbon reduction and market competitiveness amidst the global climate crisis. In this article, Stackelberg is a model game used to study the optimal decisions of various supply chain members on emission reduction strategies under various carbon labeling (CES) standards. Findings reveal that Stringent CES is beneficial when consumer low-carbon preference (CLP) is low or consumer recognition of carbon label (CLR) is pronounced. Enhancing CLR substantially boosts carbon emissions reduction, corporate performance, and environmental benefits in individual scenarios. However, improving CLP changes corporate performance, consumer surplus, and social environmental benefits are also related to CES. These insights furnishing a theoretical foundation for developing effective reduction strategies in agricultural supply chains.

Keywords: Agricultural product supply chain; Carbon reduction label standards; Low-carbon preference; Individual emission reduction; Stackelberg game.

1. Introduction

In the circumstances of global weather alteration, reducing greenhouse gas emissions is opener to sustainable development[1],and the IPCC report points out that specific carbon sources have a significant impact on global warming[2,3].Agricultural and food enterprises are adjusting their strategies to promote short-term low-carbon measures[4]. Meanwhile, governments globally have implemented measures to reduce carbon emissions within the agricultural sector[5]. As a market-based policy tool, carbon labels are gradually being integrated into countries' emission reduction strategies, and the corresponding CES formulation is crucial for accomplish effective emissions decrease in the worldwide agricultural supply chain[6]. The differences in label standards affect consumer recognition (CLR), which in turn affects the effectiveness of CES. Understanding the impact of CLR on its effectiveness is important for developing emission reduction strategies, but there is limited research on this topic. To virtually implement labeling policies, consumer demand for sustainable products is vital, and consumer low-carbon preference (CLP) is an important tool for cultivating low-carbon consumption habits[9],existing literature predominantly show CLP significantly influences carbon reduction and purchasing behavior [7,10,12,13]. In addition, CES significantly affects the emission reduction strategies and efficiency of agricultural supply chain participants. Scholars focus on the carbon reduction work of agricultural product processors[8], and existing research provides theoretical support for their diversified carbon management strategies.

This study aims to address these gaps by exploring: (1) Does CES foster carbon reduction within the agricultural supply chain, and if so, how does it influence the decision-making, overall performance, and societal benefits of supply chain members? (2) What is the impact of CLR and CLP on the effectiveness of CES? (3) How do stringent or lenient CES frameworks affect corporate profitability, as well as social and environmental benefits? By addressing these questions, this study

aims to provide a comprehensive understanding of the role CES plays in shaping carbon emission outcomes and sustainable practices within the agricultural sector.

This study employs a Stackelberg game model to analyze an agricultural supplier-processor supply chain. It investigates emission reduction scenarios where only the processor (NS model) invests in decarbonization. The supplier acts as the leader surroundings wholesale prices, while the processor affects retail prices and emission-reduction investing. The hierarchical decision-making framework is illustrated in Fig. 1.

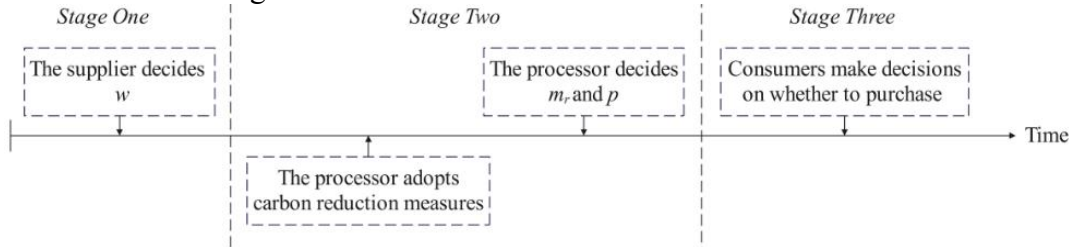


Fig. 1. Sequences of events under NS model.

Table 1 describes all parameters and variables of this study.

Table 1. Parameters and variables

Parameter	Explanation
a	Initial market demand
b	Consumer price sensitivity coefficient
β_1	Cost coefficient of emission reduction efforts or investment coefficient of emission reduction technology for processor
l_m	Maximum carbon emissions of the product
l_0	Product Carbon Emission Standards (CES)
l^{NS}	Product carbon footprint
θ_1	Consumer recognition of carbon reduction label (CLR)
θ_2	Consumer Low Carbon Preference Coefficient (CLP)
λ_i	Initial carbon emissions of enterprise i ($i=s, r$)
Decision variables	
w	Supplier wholesale price
p	Sales price of processor products
m_r	Emission reduction level
Functions	
π_i	The profit function of enterprise i ($i=s, r$)
π_{sc}	Supply chain total profit function
E	Environmental benefit function
CS	Consumer surplus function
S	Social benefit function

The market demand is expressed as [11]

$$D = a - bp + \theta_1(l_m - l_0) + \theta_2(l_0 - l^{NS}) \quad (1)$$

Environmental benefits are expressed as:

$$E = m_r * D \quad (2)$$

Consumer surplus is expressed as:

$$CS = \frac{1}{2b} * D^2 \quad (3)$$

Social benefits are expressed as:

$$S = \pi_{sc} + CS + E \quad (4)$$

2. Model construction and solution

2.1 Construction of model NS

The carbon footprint of the agricultural supply chain is defined as:

$$l^{NS} = \lambda_s + \lambda_r - m_r \quad (5)$$

The profit function of the processor is:

$$\pi_r^{NS} = (p - w) * D(l^{NS}) - \frac{1}{2} \beta_1 m_r^2 \quad (6)$$

The profit function of the supplier is:

$$\pi_s^{NS} = w * D(l^{NS}) \quad (7)$$

2.2 Solution of Model NS

According to Eqs. (1), (5), (6), and (7), the optimal decision for agricultural products can be obtained using reverse induction, as shown in Theorem 1.

Theorem 1 Under carbon labeling regulations, the optimal decision for the agricultural supply chain when processor reduces emissions separately is as follows.

The optimal wholesale price is:

$$w^{NS*} = \frac{a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)}{2b} \quad (8)$$

The optimal retail price is:

$$p^{NS*} = \frac{(3b\beta_1 - \theta_2^2)[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]}{2b(2b\beta_1 - \theta_2^2)} \quad (9)$$

The optimal carbon reduction amount is:

$$m^{NS*} = \frac{\theta_2[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]}{2(2b\beta_1 - \theta_2^2)} \quad (10)$$

The optimal demand quantity is:

$$D^{NS*} = \frac{b\beta_1[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]}{2(2b\beta_1 - \theta_2^2)} \quad (11)$$

By substituting Eqs. (8-9) into Eqs. (2-4, 6, and 7), the following approach secures peak profits for processors and suppliers while also delivering environmental, consumer, and social gains:

$$\pi_r^{NS*} = \frac{\beta_1[a + \theta_1(l_m - l_0) + \theta_2(l_0 - \lambda_s - \lambda_r)]^2}{8(2b\beta_1 - \theta_2^2)} \quad (12)$$

$$\pi_s^{NS*} = \frac{\beta_1 [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]^2}{4(2b\beta_1 - \theta_2^2)} \quad (13)$$

$$E^{NS*} = \frac{b\beta_1\theta_2 [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]^2}{4(2b\beta_1 - \theta_2^2)^2} \quad (14)$$

$$CS^{NS*} = \frac{b^2\beta_1^2 [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]^2}{8(2b\beta_1 - \theta_2^2)^2} \quad (15)$$

$$S^{NS*} = \frac{\beta_1(b^2\beta_1 - 3\theta_2^2 + 2b(3\beta_1 + \theta_2)) [a + \theta_1 (l_m - l_0) + \theta_2 (l_0 - \lambda_s - \lambda_r)]^2}{8(2b\beta_1 - \theta_2^2)^2} \quad (16)$$

Proof. Proofs are provided in Appendix A

Proposition 1 The impact of CES on optimal decision-making in scenario NS is as follows.

When $\theta_2 < \theta_1$, the following outlines CES's influence on wholesale prices, retail prices, and carbon emissions reduction:

$$\frac{\partial w^{NS*}}{\partial l_0} < 0, \frac{\partial p^{NS*}}{\partial l_0} < 0, \frac{\partial m^{NS*}}{\partial l_0} < 0 \quad (17)$$

When $\theta_2 < \theta_1$ is present, the impacts of CES on the profits of processors and suppliers, environmental benefits, consumer surplus, and social benefits are as follows:

$$\frac{\partial \pi_r^{NS*}}{\partial l_0} < 0, \frac{\partial \pi_s^{NS*}}{\partial l_0} < 0, \frac{\partial E^{NS*}}{\partial l_0} < 0, \frac{\partial CS^{NS*}}{\partial l_0} < 0, \frac{\partial S^{NS*}}{\partial l_0} < 0 \quad (18)$$

Proof. Proofs are provided in Appendix A.

3. Case study and discussion

Taking the radish supply chain as the empirical research object, based on the morphological feature grading system (high-quality/ordinary/small/defective), the analysis is carried out, and the supply chain members cover core links such as planting, harvesting, sorting and processing. Research shows that planting, harvesting, and processing are the main sources of carbon emissions, with a unit yield carbon emission of 2000 kg CO₂ eq/t (700 kg CO₂ eq/t from suppliers and 800 kg CO₂ eq/t from processors). To evaluate the effectiveness of carbon emission reduction labeling standards (CES) in enhancing sustainability, a comparative analysis was conducted between strict ($l_0 = 10$ kg CO₂ eq/t) and relaxed ($l_0 = 1000$ kg CO₂ eq/t) CES scenarios. The green investment cost coefficient of 1, CLR=0.8, and CLP=0.4 were set as benchmark parameters to verify the dynamic coupling relationship of the low-carbon supply chain.

3.1 Analysis of the impact of CLR

CLR is a key gauge of consumer confidence that shapes purchasing through perceived sustainability. Stronger government engagement in CES boosts institutional credibility and market recognition of certified low-carbon products, creating a virtuous cycle where strict regulation and consumer trust mutually propel sustainable consumption.

As depicted in Fig. 2 (a), an increase in CLR (θ_1) is linked to greater emission reductions throughout the supply chain. Compared to laxer standards, stricter emission standards always lead to greater emissions reductions when CLR increases to a certain extent.

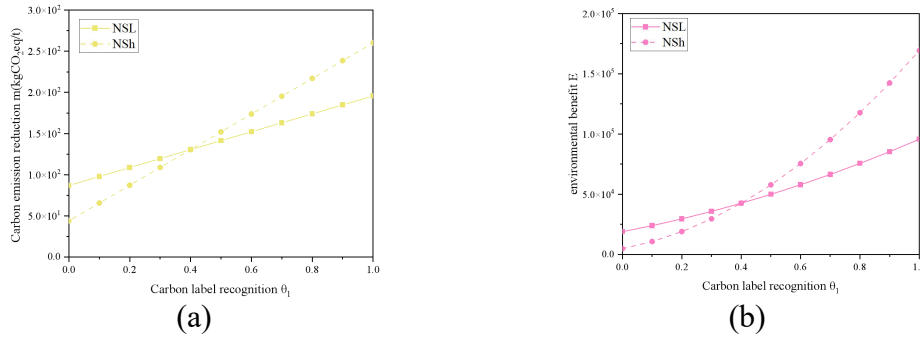


Fig. 2. The impact of CLR on carbon reduction and environmental benefits under two CES.

Fig. 2 (b) links CLR growth to environmental gains: strict standards under high CLR boost low-carbon demand, label credibility, and innovation, improving market/emission efficiency for superior outcomes.

Fig. 3 analyzes CLR-CES interaction: stringent CES boosts welfare under high CLR but reduces it with weak CLR, highlighting policy-market synergy and imbalance risks.

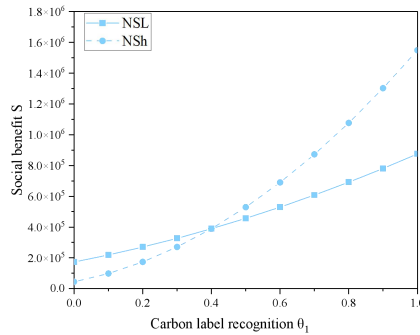


Fig. 3. The impact of CLR on social benefit under two types of CES.

3.2 Analysis of the impact of CLP

CLP can also affect business decision-making, as it represents the green level of the marketing environment. A larger CLP indicates that consumers have higher environmental awareness and are more willing to purchase green products.

Fig. 4 (a) shows stringent CES yields higher NS carbon reductions at low CLP but lower at high CLP versus relaxed CES. Both models rise with CLP growth. High CLP drives low-carbon demand, while relaxed CES expands market reach, stimulating corporate emission cuts and broader impact.

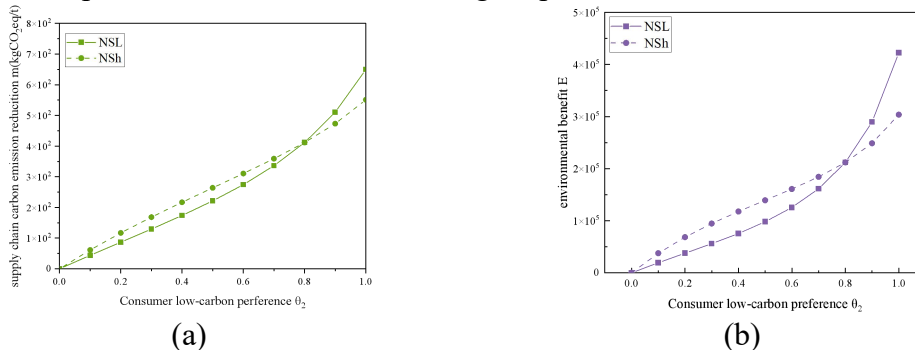


Fig. 4. Impact of CLP on carbon reduction and environmental benefits under two CES.

Fig. 4 (b) reveals stringent CES yields higher environmental benefits at low CLP but underperforms relaxed CES when CLP increases. Both strategies improve with rising CLP. High CLP drives low-carbon demand under relaxed CES by lowering certification barriers, expanding product availability, stimulating emission controls, and amplifying carbon reduction outcomes.

Fig. 5 delineates a nuanced relationship between CLP (θ_2) and CES (l_0) on the social benefits of the NS model. At lower CLP, strict CES yields higher social benefits than relaxed CES. At higher CLP, social benefits are lower under strict CES.

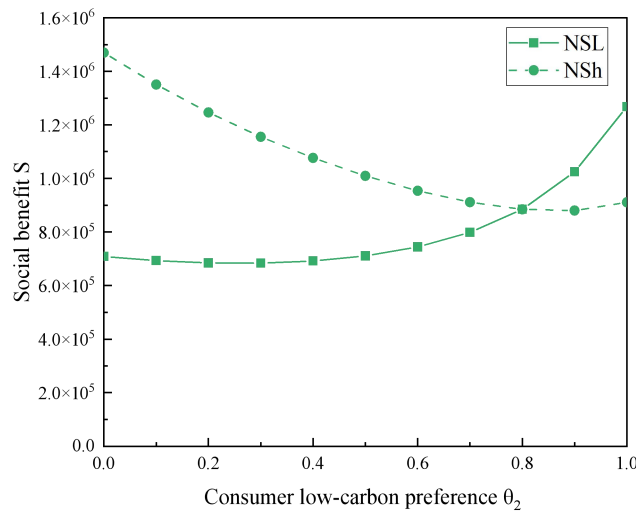


Fig. 5. The impact of CLP on social benefits under two types of CES.

The heightened CLP drives low-carbon product demand; relaxed CES lowers certification barriers, expanding their market reach. This enables more firms to produce low-carbon products at lower costs, propelling environmental sustainability. This transition decreases carbon emissions, encourages the adoption of green technologies, improves environmental and social well-being, and boosts societal benefits.

4. Conclusions

This study analyzes the mechanism of CES on the profitability and operational efficiency of agricultural supply chain members through a Stackelberg game model, and constructs a multi-agent decision-making framework to reveal that the supply chain achieves sustainable development and economic benefits through optimized emission reduction synergy under the constraints of carbon labeling policies. The model compares the decision-making behavior and performance of suppliers and processors under different CES, and draws core conclusions.

Our research shows that under strict CES regulation, high CLR levels significantly improve supply chain carbon reduction performance and overall environmental and social benefits, bringing higher economic returns through product differentiation and market competitiveness; At the same time, CLP, as a key incentive, may initially reduce some profits and social benefits, but ultimately promote systemic decarbonization. Processors' emission reduction efforts also raise consumers' environmental awareness through feedback mechanisms. Case study proves that compared with loose policies, strict regulation combining CES, CLR, and CLP can better promote the sustainable transformation of the supply chain, and enterprises should formulate wiser emission reduction strategies based on this.

This study proposes the following strategic recommendations: policy makers should moderately increase CLP under strict CES regulation to support companies in reducing emissions and gaining environmental and social benefits. However, caution should be taken to consider that the improvement of CLP can not only improve environmental outcomes but may also affect profits and social benefits. Therefore, when CLP is high, loose CES can be appropriately adopted to optimize corporate profits and social advantages; Enterprises should prioritize implementing deep carbon reduction when the CLR rises, obtain market premiums through carbon label certification, and achieve a positive cycle of "high CLR - strict emission reduction-high return". Meanwhile, tailor the CES strategy according to the CLP level to balance brand reputation and price competitiveness;

consumers must boost their low-carbon consumption awareness, foster systematic emission reductions and integrated environmental benefits, and establish a positive dynamic between market forces and institutional refinement.

5. Acknowledgements

This work was supported by the Natural Science Foundation of Hebei Province (G2024502001), the Research Foundation of China University of Petroleum-Beijing at Karamay (NO. XQZX20250010), and the Fundamental Research Funds for the Central Universities (2024MS161).

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