Carbon-Trade Price Influence on CarbonRegulation of Tobacco Supply Chain

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Carbon emissions exist in all links of tobacco SC, among whichtobacco, acetic acid tow and cigarette production are important links of cigarette carbon emission.Under the background of green economic development, it is very significant to study the coordinated development of economy and environment from the angle of tobacco SC.Carbon-trade is aneffectivechannel to realize reducing carbon emissions by using market mechanism.Take into consideration grandfathering and the goal of carbon regulation, game models of SCwith carbon trading are established. We analyze the influence of three factors including carbon-trade price, decision-making mode, technology emission reduction investment on the degree of carbon regulation and SC profits, the conclusions are verified by numerical illustration. The research shows that: without investment of technology, the three different decision-making modescarbon regulation degreeare the same. In the investment of technology emission reduction, the degree of carbon regulation is the strictest under the centralized decision-making mode while the most relaxed under the retailer led decision-making mode. Different carbon-trade prices have different effects on the investment decisions of three different decision-making modes; technology investment in decentralized decision-making is always conducive to retailer and the total profits.

Keywords: tobacco SC;carbon-trade price; carbon regulation

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At present, the tobacco industry is still an industry with high carbon emissions. There are many greenhouse gas emissions in the whole tobacco supply chain (SC) from production to after-sales. For example, the large use of pesticides and chemical fertilizers during flue-cured tobacco planting will produce more greenhouse gases, and the use of some machinery and energy in the tobacco industry will produce carbon emissions.Tobacco, acetic acid tow and cigarette production are important links of cigarette carbon emission.[1-3]Therefore, from the angle of tobacco SC, coordinated development of tobacco industry in economy and environment have the important practical significance.

Due to the shortcomings of administrative methods, carbon regulators prefer to use market means to reduce carbon emissions.Enterprises are the main body to achieve carbon emission reduction and regional economic coordination. However, under the implementation of "bottom-up" independent emission reduction mechanism in the Paris Agreement, if we only focus on a single enterprise, we will not be able to effectively solve the problem of cooperation between upstream and downstream enterprises, then the carbon emission reduction cannot be fundamentally promoted. Therefore, studying carbon emission reduction is more advantageous to achieve the ultimate comprehensivegoal from SC.[4]

Under such a low-carbon background, how well does carbon-trade price regulate carbon of tobacco SC with different decision-making models? How the carbon-trade priceaffects decision-making mode and the choice of low-carbon technology of tobacco SC? The research and solution of these issues is very significance to the choice of carbon regulatory mode and effective tobacco carbon emission reduction.

LITERATURE REVIEW

Carbon trading mechanism promotes enterprises to strengthen R & D and adopt new technologies and equipment to cut carbon emissions in the production process through market means. Many scholars have studied carbon trading to optimize the operation strategies of enterprises and obtain competitive advantages in the low-carbon economic environment. Subramanian et al. studied the optimal carbon reduction investmentand revenue-sharing contract of manufacturer under the carbon trading mechanism by establishing a three-stage game model.[3]According to the carbon footprint parameters, Benjaafar et al. establishedoptimization models to research the impact of enterprise cooperation on cost and carbon emissions of SC.[5] He et al. studied the effect of carbon-trade mechanism on bulk ordering on SC.[6] Chang et al. studied the impact of carbon-trade mechanism of SC recycling and remanufacturing.[7] Song et al.studied the influence of the carbonsharing regulation of surplusemission quotas among SC on SC performance.[8]Yenipazarlistudied manufactureroptimal decisions under the carbon-trade mechanism.[9]Chen et al. analyzed the mechanism of carbon-trade price on manufacturer' unit carbon emissions.[10]Through the optimal decision model of SC, Du et al. find that the cap-and-trade would can effectively promote low-carbon production.[11]Liu et al. studied that under the condition of retailer led carbon-trade, suppliers and retailer jointly determine the wholesale price, which can realize the optimal cooperative emission reduction mechanism of the SC.[12]Kosnikshows that cap-and-trade have more advantages than carbon tax.[13]

The above literatures have conducted in-depth research on the problems caused by the SC carbon exchange, and have contributed greatly to the research in this field. The exogenous price of carbon plays akeyrole in carbon regulation, and many researches focus on the optimal coordinationmechanism under a givencarbon-trade price. [7]Few people consider the impact of carbon-trade price on the decision-making mode of SC, the selection of low-carbon technology and the degree of carbon regulation. At the same time, no matter whether it iscarbon-tradeor carbon tax, the goal of carbon emission reduction has been achieved, and the formulation of this target should depend on historical carbon emissions. According to the results of the model, this paper will study the influence of carbon-trade price on low-carbon technology emission reduction options, SC decision-making models, and the degree of carbon regulation.

The conclusions of this paper tell us that under a certain carbon-trade price, based on the grandfathering law, if the SC does not invest in technology reduction, the SC decision-making mode has no effect on carbon reduction. In the case of technology emission reduction investments, the extent of the carbon cap under the retailer's decision modeis morebeneficial to SC.

MATHEMATICAL MODEL

Suppose the SC consists of only a manufacturer and a retailer, the commodityretail price is$p$ while wholesale price is$w$, the unit product cost is c, the unit product carbon emissions is e. According to Toptal et al., the market demand is $a-p$, where a is a market base[14]. When carbon emission reduction is not considered, manufacturer and retailer profits functions are $(w-c)(a-p)$ and $(p-w)(a-p)$.The optimal output is$(a-c)/2$ under centralized decision-making mode, while the optimal output is $(a-c)/4$ in the decentralized decision-makingregardless of whether it is manufacturer-led or retail-led. Then the carbon emissions of the SC is $(a-c)\,e\,/\,2$ in centralized decision-making, and the carbon emissions is $(a-c)\,e\,/\,4$ in decentralized decision-making.

Grandfathering means allocation based on the enterprise's past carbon emissions, so the carbon limit under the centralized decision-making mode is $K^{\mathrm{C}}=\alpha(a-c)e/2$, the carbon limit is $K=\alpha(a-c)e/4$ of the decentralized decision-making mode, where α is a positive carbon cap extent parameter. Then the carbon emissions that the SC needs to buy are $b\left((a-p)e-K^{\mathrm{C}}\right)$ under centralized decision-making mode, where b is the carbon price per product. When $K^{\mathrm{C}}-(a-p)e>0$, the SC can benefit by reselling the remaining carbon emissions. Instead, SC purchases are positive payments for insufficient carbon emissions.Similarlythe carbon emissions that the SC needs to buy at this time are $b\big((a-p)e-K\big)$ decentralized decision-making mode.

Investment in technology reduction can enable enterprises to reduce the carbon emissions of individual products and increase production while meeting carbon quotas. Suppose that unit productcarbon emissions is reduced from e to x after implementation of low-carbon technology. The investment cost for technology emission reduction is $\gamma(e-x)^2$ according to the AJ model, where γ is a positive emission reduction cost coefficient. [15]

Let E^ibe the overall carbon emissions, π^i be the totalprofitsof the SC in i mode, and π_j^i is the profitsof j in i mode, where superscript $i=C,M,R$ respectively represent the situation under centralized decision-making, manufacturer-led, and retail-led, the superscript T represents the low-carbon technology emission reduction situation, and $j=M,R$ representsmanufacturer and retailer.

Without considering the investmentlow-carbon technology, in the decentralized decision model, the objective profits functions of manufacturer and retailer are:

$$\max\pi_{\mathrm{M}}(w)=(w-c)(a-p)+b(K-(a-p)e)\quad(1)$$

$$\max\pi_{\mathrm{R}}(p)=(p-w)(a-p)\quad(2)$$

In centralized decision-making mode, total profits ofSC are respectively:

$$\max\pi^{C}(p)=(p-c)(a-p)+b(K^{\mathrm{C}}-(a-p)e)\quad(3)$$

When considering the investment of low-carbon technology inSC, in the decentralized decision model, the objectiveprofitsfunctionsare as follows:

$$\max\pi_{\mathrm{M}}(w,x)=(w-c)(a-p)+b(K-(a-p)x)-\gamma(e-x)^2/2\quad(4)$$

$$\max\pi_{\mathrm{R}}(p)=(p-w)(a-p)\quad(5)$$

In centralized decision-making model, SC's total profits are respectively:

$$\max\pi^{C}(p,x)=(p-c)(a-p)+b(K^{\mathrm{C}}-(a-p)e)\quad(6)$$

As the manufacturer led SC, manufacturer has the first-mover advantage to determine the$w$ and the$x$, the retailer determines p according to the manufacturer's decision. For retail-led SC, the decision-making steps is opposite.

COMPARATIVE ANALYSIS

When there is no technology emission reduction investment, for differentSC decision-making models, does the same carbon-trade price have the same degree of carbon cap? If the SC is investing in technology reduction, will the same carbon-trade pricein accord withthe carbon caps of the SC for different decision-making models? If there are inconsistencies, how will carbon-trade prices affect the extent of carbon caps and unit product carbon emissions in different decision-making models? Based on these issues, we come to the following conclusions.

Proposition 1:Without considering the investment of technology emission reduction, the degree of carbon regulation is equal, that is $\alpha=\alpha^{\mathrm{C}}=\alpha^{\mathrm{M}}=\alpha^{\mathrm{R}}=\frac{a-c-et}{a-c}$.

The proof process of proposition 1 is shown in Appendix.

When there is no investment in technology emission reduction, carbon-trade prices have the same degree of carbon regulation,it indicates that in the absence of technology emission reduction, the leading mode of SC has no effect on the degree of carbon limitation

Proposition 2: $\alpha^{\mathrm{TR}} > \alpha^{\mathrm{TM}} > \alpha^{\mathrm{TC}}$

The proof process of proposition 2 is shown in Appendix.

The numerical illustration of the result of proposition 2 is shown in Figure 1. This proposition shows that in the case of technology emission reduction investment, the dominant model of the SChas different effects on the degree of carbon regulation.

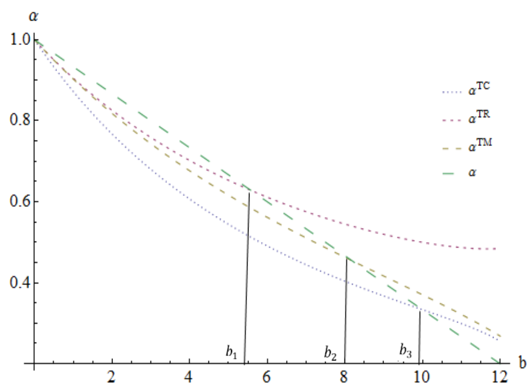

Figure 1 The impact of carbon-trade priceon the extent of carbon limit

Proposition 3: There exists $b_3 > b_2 > b_1 > 0$, so that: When $b \le b_1, \alpha \ge \alpha^{\mathrm{TR}} > \alpha^{\mathrm{TM}} > \alpha^{\mathrm{TC}}$; when $b_1 < b \le b_2, \alpha^{\mathrm{TR}} > \alpha \ge \alpha^{\mathrm{TM}} > \alpha^{\mathrm{TC}}$; when $b_2 < b \le b_3, \alpha^{\mathrm{TR}} > \alpha^{\mathrm{TM}} > \alpha \ge \alpha^{\mathrm{TC}}$; when$b > b_3$, $\alpha^{\mathrm{TR}} > \alpha^{\mathrm{TM}} > \alpha^{\mathrm{TC}} > \alpha$.

The proof process of proposition 3 is shown in Appendix.

The numerical illustration result of proposition 3 is shown in Figure 1, which indicates that the carbon-trade price is an important element that affects whether the SC invests in technology emission reduction. When the carbon-trade price is less than b_1, the SC carbon is most loosely regulated when there is no technical emissionreduction at the same carbon-trade price. When the carbon-trade price is greater than b_3, the degree of carbon regulation in the SC is the most lenient when technology is reducing emissions under the same carbon-trade price.

Proposition 4:$x^{\mathrm{TC}} < x^{\mathrm{TR}} < x^{\mathrm{TM}}$.

The proof process of proposition 4 is shown in Appendix.

The numerical illustrationresult of proposition 4 is shown in Figure 2. Itshows that under the condition of a certain carbon-trade price when technology investment is reduced, different SC-dominated modes have different effects on carbon emissions per unit product, it is the largest when the manufacturer is dominant, while it is the smallest of the centralized decision mode.

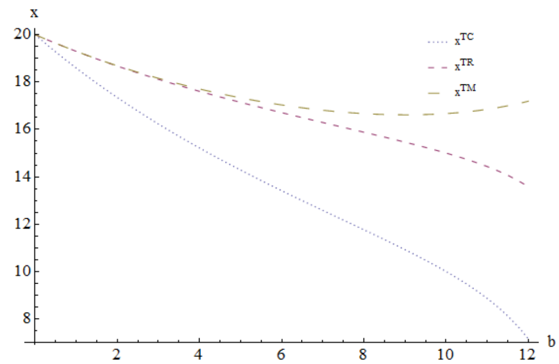

Figure 2The influence of carbon-trade price on unit product carbon emission with technology investment

Proposition 5:

(1)$\pi_{\mathrm{R}}^{\mathrm{TR}} > \pi_{\mathrm{R}}^{\mathrm{R}}$,$\pi_{\mathrm{R}}^{\mathrm{TM}} > \pi_{\mathrm{R}}^{\mathrm{M}}$.

(2) When $b > b_4$, $\pi_{\mathrm{M}}^{\mathrm{TM}} > \pi_{\mathrm{M}}^{\mathrm{M}}$; when$b \le b_4$,$\pi_{\mathrm{M}}^{\mathrm{TM}} \le \pi_{\mathrm{M}}^{\mathrm{M}}$. Where b_4 is given by $(b^2 + 4\gamma)A + 2be(b^2 - 4\gamma) = 0$;

When$b > b_5$, $\pi_{\mathrm{M}}^{\mathrm{TR}} > \pi_{\mathrm{M}}^{\mathrm{R}}$; when $b \le b_5$, $\pi_{\mathrm{M}}^{\mathrm{TR}} \le \pi_{\mathrm{M}}^{\mathrm{R}}$. Where b_5 is given by$(b^2 + 2\gamma)A + 4be(b^2 - 2\gamma) = 0$.

(3) $\pi^{\mathrm{TM}} > \pi^{\mathrm{M}}$, $\pi^{\mathrm{TR}} > \pi^{\mathrm{R}}$. When $b > b_6$, $\pi^{\mathrm{TC}} > \pi^{\mathrm{C}}$; when $b \le b_6$, $\pi^{\mathrm{TC}} \le \pi^{\mathrm{C}}$. Where$b_6$ is given by $(b^2 + 2\gamma)A + 2be(b^2 - 2\gamma) = 0$.

The proof process of proposition 5 is shown in Appendix.

The simulation of proposition 5 is shown in Figures 3 to 5. This proposition shows that whether the SC is dominated by manufacturer or retailer, technology emission reduction investment is always goodfor retailer. In decentralized decision-making, technology emission reduction investment is always beneficial to the total profitsof the SC. In centralized decision-making, whether technology investment conduciveto the SC is related to the carbon-trade price. When the carbon-trade price is higher than a certain threshold, technology emission reduction investment will be more beneficial to the SC. Similarly, in decentralized decision-making, whether it is a manufacturer-led or retail-led SC, when carbon-trade price is a threshold, technology emission reduction investment will be more conducive to manufacturer.

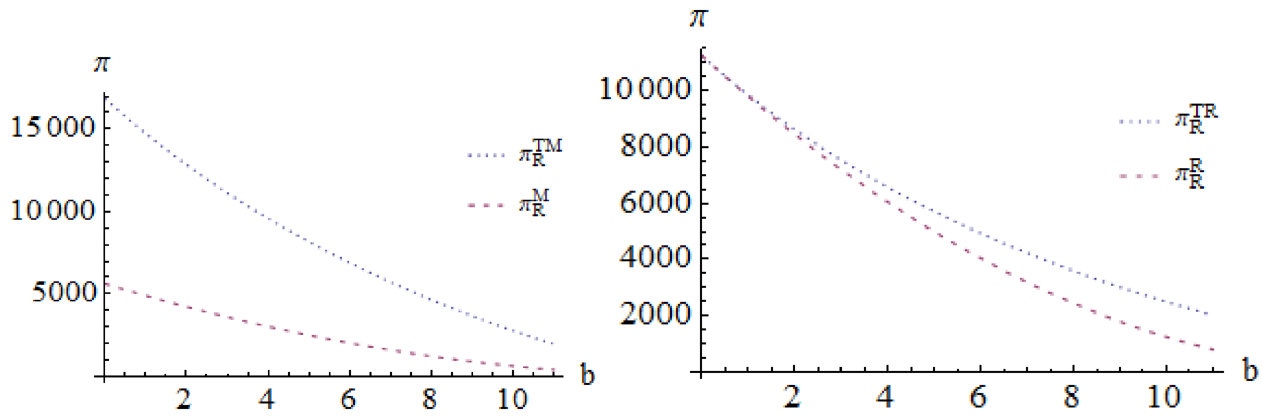

Figure 3 Comparison of retailer's profitsunder the condition of manufacturer leading and retailer leading with or without technology investment

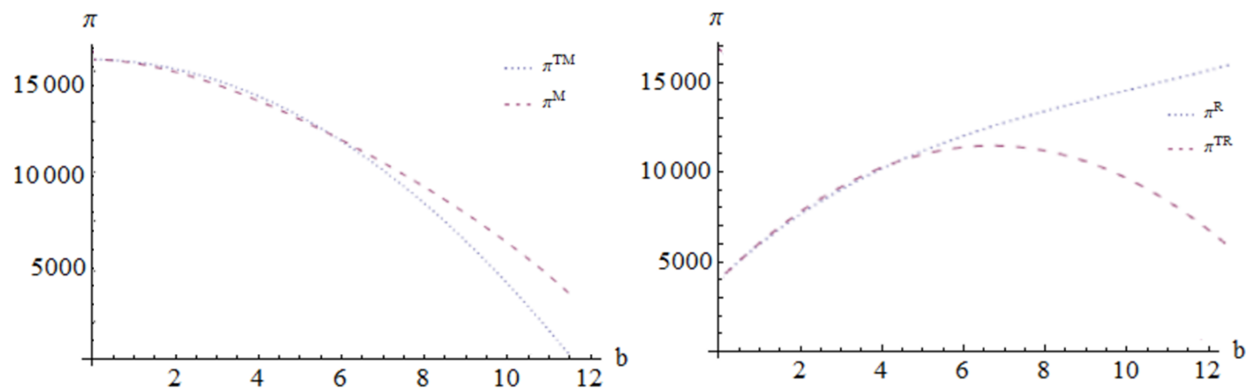

Figure 4 Manufacturer's profitscomparison between manufacturer led and retailer led with or without technology investment

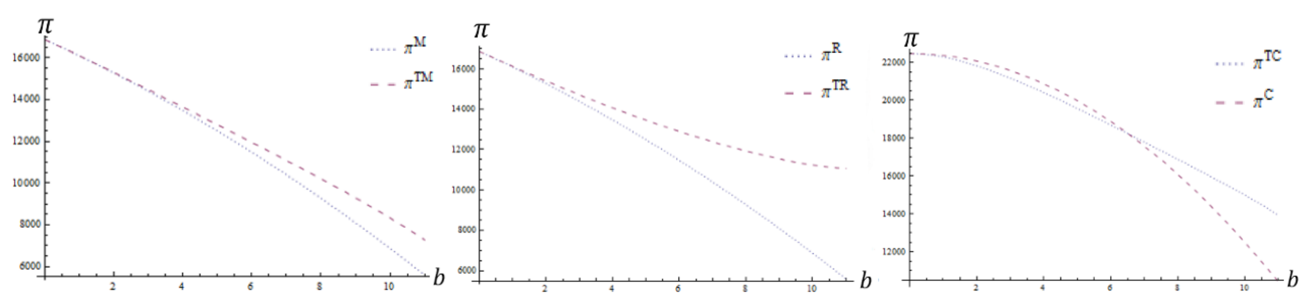

Figure 5 Comparison of the total profits of the SC with or without technology investment

CONCLUSION

This article sets the overall goal of carbon regulation and emission reduction based on the historically optimal output of thetobaccoSC, establishes carbon-trade SCgame models of manufacturer-dominated, retailer-dominatedand centralized decision-making with or without technology investment. The optimal decision results analyze the impact of carbon-trade price, SC decision-making models, and technology emission reduction investments on the degree of carbon regulation and SC profits, and the conclusions are verified through simulation. The research shows that when the carbon-trade price is a constant, for three different decision modes, the degree of carbon regulation is the same when there is no technology emission reduction investment, and under the centralized decision mode when technology emission reduction investment is made, the carbon regulation is the strictest and the retailer-led decision mode carbon regulation is the most lenient; different carbon-trade prices have different impacts on technology emission reduction investment decisions for three different decision modes; technology investment emission reductions in decentralized decisions are always beneficial to retailer and overall revenue. Whether it is beneficial to manufacturer depends on carbon-trade price. In this paper, through quantitative research, we discovered the impact of carbon-trade prices on the degree of carbon regulation of different decision-making types of SC and incentives for technology investment emission reduction.

Study Limitations

Because this article only considers the secondary SC formed by one manufacturer and one retailer, for manufacturer, there are often multiple raw materials suppliers for carbon raw materials upstream processing. Then in such a three-tiertobacco SC, how the carbon-trade price will affect carbon regulation will be a question for further research in the later stage.

APPENDIX

A.Proof of Proposition 1.

Without considering technology investment, for the centralized decision-making model, the carbon limit for this model is based on historical output. According to formula (3), since $\frac{\partial^2\pi^{\mathrm{C}}}{\partial p^2}=-2<0$,$\pi^{\mathrm{C}}$ has a maximum value. According to the first-order condition $\frac{\partial\pi^{\mathrm{C}}}{\partial p}=0$,obtained$p^{\mathrm{C}}=\frac{1}{2}(a+c+eb)$,so that $\pi^{\mathrm{C}}=\frac{1}{4}A^2+\frac{1}{4}b(a-c)e\alpha, E^{\mathrm{C}}=\frac{1}{2}Ae$. According to $E^{\mathrm{C}}-K^{\mathrm{C}}=0, \alpha^{\mathrm{C}}=\frac{A}{a-c}$ is obtained. Substituting it into π^{C} gives $\pi^{\mathrm{C}}=\frac{1}{4}A(A+2be)$, where $A=a-c-et$.

In the manufacturer-dominated model, the carbon limit is K, which is solved inversely according to the Stackelberg model. For calculation convenience, let$r=p-w$. According to formula (2), since $\frac{\partial^2\pi_{\mathrm{R}}^{\mathrm{M}}}{\partial r^2}=-2<0, \pi_{\mathrm{R}}^{\mathrm{M}}$ has a maximum value. According to its first derivative $\frac{\partial\pi_{\mathrm{R}}^{\mathrm{M}}}{\partial r}=a-2r-w=0$,we get $r=\frac{a-w}{2}$, which is substituted into equation (1),$\frac{\partial^2\pi_{\mathrm{M}}^{\mathrm{M}}}{\partial w^2}=-1<0$,so $\pi_{\mathrm{M}}^{\mathrm{M}}$ has a maximum value. According to $\frac{\partial\pi_{\mathrm{M}}^{\mathrm{M}}}{\partial w}=0, w=\frac{1}{2}(a+c+be), \pi_{\mathrm{M}}^{\mathrm{M}}=\frac{1}{8}A^2+\frac{1}{4}(a-c)^2(1-\alpha)\alpha, \pi_{\mathrm{R}}^{\mathrm{M}}=\frac{1}{16}A^2, \pi^{\mathrm{M}}=\frac{3}{16}A^2+\frac{1}{4}(a-c)^2(1-\alpha)\alpha, E^{\mathrm{M}}=\frac{1}{4}Ae$. According to $K-E^{\mathrm{M}}=\alpha\frac{a-c}{4}e-(\frac{1}{4}eA)=0, \alpha^{\mathrm{M}}=\frac{A}{a-c}$ is obtained. At this time, $\pi_{\mathrm{M}}^{\mathrm{M}}=\frac{1}{8}A(A+2be), \pi^{\mathrm{M}}=\frac{3}{16}A^2+\frac{1}{4}Abe$.

In the retailer-dominated model, the carbon limit is K calculated in reverse using the Stackelberg model. According to formula (1),since $\frac{\partial^2\pi_{\mathrm{M}}^{\mathrm{R}}}{\partial w^2}=-2<0, \pi_{\mathrm{M}}^{\mathrm{R}}$ has a maximum value. According to its first derivative $\frac{\partial\pi_{\mathrm{M}}^{\mathrm{R}}}{\partial w}=a+c+eb-2w-r=0$,we get $w=\frac{1}{2}(a+c+eb-r)$ and substitute it into equation (2),$\frac{\partial^2\pi_{\mathrm{R}}^{\mathrm{R}}}{\partial r^2}=-1<0$,so $\pi_{\mathrm{R}}^{\mathrm{R}}$ has a maximum value. According to $\frac{\partial\pi_{\mathrm{R}}^{\mathrm{R}}}{\partial r}=\frac{1}{2}(a-c-2r-eb)=0, r=\frac{1}{2}A$ is obtained, and $\pi_{\mathrm{M}}^{\mathrm{R}}=\frac{1}{16}A^2+\frac{1}{4}(a-c)^2(1-\alpha)\alpha, \pi_{\mathrm{R}}^{\mathrm{R}}=\frac{1}{8}A^2, \pi^{\mathrm{R}}=\frac{3}{16}A^2+\frac{1}{4}b(a-c)e\alpha, E^{\mathrm{R}}=\frac{1}{4}eA$. According to $K_B-E^{\mathrm{R}}=0$, get $\alpha^{\mathrm{R}}=\frac{A}{a-c}$. Thus, $\pi_{\mathrm{M}}^{\mathrm{R}}=\frac{1}{16}A^2+\frac{1}{4}Abe, \pi^{\mathrm{R}}=\frac{3}{16}A^2+\frac{1}{4}Abe$.

From the above models, it can be seen that the degree of carbon regulation α all are $\frac{A}{a-c}$.

B.Proof of Proposition 2.

Considering the technology emission reduction investment, in the centralized decision mode, according to formula (6), since $\frac{\partial^2\pi^{\mathrm{TC}}}{\partial p^2}\frac{\partial^2\pi^{\mathrm{TC}}}{\partial x^2}-(\frac{\partial^2\pi^{\mathrm{TC}}}{\partial x\partial p})^2=-b^2+2\gamma, \frac{\partial^2\pi^{\mathrm{TC}}}{\partial p^2}=-2, \frac{\partial^2\pi^{\mathrm{TC}}}{\partial x^2}=-\gamma$. When $-b^2+2\gamma>0$, there is a maximum value, let $\frac{\partial \pi^{\mathrm{TC}}}{\partial p}=0, \frac{\partial \pi^{\mathrm{TC}}}{\partial x}=0$ to get $p=-\frac{(c+be)\gamma+a(-b^2+\gamma)}{b^2-2\gamma}, x^{\mathrm{TC}}=e-\frac{Ab}{B}$ to get $\pi^{\mathrm{TC}}=\frac{1}{4B}(2A^2\gamma+b(B(a-c))e\alpha), E^{\mathrm{TC}}=\frac{A(Be-Ab)\gamma}{B^2}$, according to $E^{\mathrm{TC}}-K^{\mathrm{C}}=0$, we obtain $\alpha^{\mathrm{TC}}=\frac{\frac{2A(Be-Ab)\gamma}{B^2(a-c)e}}{}$, so that $\pi^{\mathrm{TC}}=\frac{A\gamma(BA+2b(Be-Ab))}{2B^2}$.,where $B=-t^2+2\gamma$.

When manufacturer-led SC, a reverse solution is adopted according to the Stackelberg model. According to formula (5), since $\frac{\partial^2 \pi_{\mathrm{R}}^{\mathrm{TM}}}{\partial r^2}=-2<0$, its first derivative $\frac{\partial \pi_{\mathrm{R}}^{\mathrm{TM}}}{\partial r}=a-2r-w=0$, get $r=\frac{a-w}{2}$, substituting into equation (4), because $\frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{TM}}}{\partial w^2}=-1, \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{TM}}}{\partial x^2}=-\gamma, \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{TM}}}{\partial w^2}\frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{TM}}}{\partial x^2}-\left(\frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{TM}}}{\partial w \partial x}\right)^2=-\frac{b^2}{4}+\gamma$, so there is a maximum value when $b^2-4\gamma<0$. According to $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{TM}}}{\partial w}=0, \frac{\partial \pi_{\mathrm{M}}^{\mathrm{TM}}}{\partial x}=0$, we get $w=\frac{a(b^2-2\gamma)-2(c+be)\gamma}{b^2-4\gamma}$, so that $x^{\mathrm{TM}}=\frac{Be-Ab+2e\gamma}{B+2\gamma}, \pi_{\mathrm{M}}^{\mathrm{TM}}=-\frac{1}{4(b^2-4\gamma)}(b^3ce\alpha+2a^2\gamma+2c^2\gamma+2b^2e^2\gamma-4bce(-1+\alpha)\gamma-a(b^3e\alpha+4c\gamma-4be(-1+\alpha)\gamma)), \pi_{\mathrm{R}}^{\mathrm{TM}}=\frac{A^2\gamma^2}{(B+2\gamma)^2}, \pi^{\mathrm{TM}}=-\frac{1}{4(b^2-4\gamma)^2}(b^5ce\alpha+2b^4e^2\gamma+4b^3ce(1-2\alpha)\gamma+2a^2(b^2-6\gamma)\gamma-12c^2\gamma^2+8bce(-3+2\alpha)\gamma^2+2b^2\gamma(c^2-6e^2\gamma)-a(b^5e\alpha+4b^2c\gamma+4b^3e(1-2\alpha)\gamma-24c\gamma^2+8be(-3+2\alpha)\gamma^2)), E^{\mathrm{TM}}=\frac{A\gamma(Be-Ab+2e\gamma)}{(B+2\gamma)^2}$.
Since the carbon limit $K=\alpha\frac{a-c}{4}e$, according to $K-E^{\mathrm{TM}}=\alpha\frac{a-c}{4}e-\frac{A\gamma(Be-Ab+2e\gamma)}{(B+2\gamma)^2}=0$, we obtain $\alpha^{\mathrm{TM}}=\frac{4A\gamma(Be-Ab+2e\gamma)}{(a-c)e(B+2\gamma)^2}, \pi_{\mathrm{M}}^{\mathrm{TM}}=\frac{A\gamma((3A+2be)(B+2\gamma)-8A\gamma))}{2(B+2\gamma)^2}$, $\pi^{\mathrm{TM}}=\frac{A\gamma((3A+2be)(B+2\gamma)-6A\gamma)}{2(B+2\gamma)^2}$.

When retailer-led SC, according to the Stackelberg model, the reverse solution is adopted. According to formula (4), since $\frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{TR}}}{\partial w^2}=-2<0, \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{TR}}}{\partial x^2}=-\gamma<0, \frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{TR}}}{\partial w^2}\frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{TR}}}{\partial x^2}-\left(\frac{\partial^2 \pi_{\mathrm{M}}^{\mathrm{TR}}}{\partial w \partial x}\right)^2=-b^2+2\gamma>0$, so $\pi_{\mathrm{M}}^{\mathrm{TR}}$ has a maximum value. According to its first derivative $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{TR}}}{\partial w}=0$ and $\frac{\partial \pi_{\mathrm{M}}^{\mathrm{TR}}}{\partial x}=0$, we get $w=-\frac{(a+c-r)\gamma+b(-ab+br+e\gamma)}{b^2-2\gamma}, x=\frac{ab-b(c+r)-2e\gamma}{b^2-2\gamma}$.
Substituting into the formula $\pi_{\mathrm{R}}^{\mathrm{TR}}$ gives $\frac{\partial^2 \pi_{\mathrm{R}}^{\mathrm{TR}}}{\partial r^2}=\frac{2\gamma}{b^2-2\gamma}<0$, so $\pi_{\mathrm{R}}^{\mathrm{TR}}$ has a maximum value. According to the first derivative,We get $w=\frac{(c+be)(b^2-3\gamma)+a(b^2-\gamma)}{2(b^2-2\gamma)}, x^{\mathrm{TR}}=\frac{2eB-Ab}{2B}, \pi_{\mathrm{M}}^{\mathrm{TR}}=-\frac{2b^3ce\alpha+a^2\gamma+c^2\gamma+b^2e^2\gamma+2bce(1-2\alpha)\gamma-2a(b^3e\alpha+c\gamma+be(1-2\alpha)\gamma)}{8(b^2-2\gamma)}, \pi_{\mathrm{R}}^{\mathrm{TR}}$ $\frac{A^2\gamma}{4B}$, $\pi^{\mathrm{TR}}=-\frac{1}{8(b^2-2\gamma)}(2b^3ce\alpha+3a^2\gamma+3c^2\gamma+3b^2e^2\gamma+2bce(3-2\alpha)\gamma-2a(b^3e\alpha+3c\gamma+be(3-2\alpha)\gamma)), E^{\mathrm{TR}}=\frac{A\gamma(2eB-Ab)}{4B^2}$. Since the carbon limit $K=\alpha\frac{a-c}{4}e$, according to $K_B-E_{\mathrm{R}}^{\mathrm{T}}=0$, we get $\alpha^{\mathrm{TR}}=\frac{A\gamma(2eB-Ab)}{(a-c)eB^2}$, so that $\pi_{\mathrm{M}}^{\mathrm{TR}}=\frac{A\gamma((3A+4be)B-4A\gamma)}{8B^2}, \pi^{\mathrm{TR}}=\frac{A\gamma((5A+4be)B-4A\gamma)}{8B^2}$.

Since $\alpha^{\mathrm{TR}}-\alpha^{\mathrm{TC}}=\frac{A^2\gamma b}{B^2(a-c)e}>0, \alpha^{\mathrm{TM}}-\alpha^{\mathrm{TC}}=\frac{2bA\gamma(b(B+2\gamma)(Be-Ab)+4BA\gamma)}{(B(B+2\gamma))^2(a-c)e}>0$,so $\alpha^{\mathrm{TR}}>\alpha^{\mathrm{TC}}, \alpha^{\mathrm{TM}}>\alpha^{\mathrm{TC}}$. According to $Be>Ab, 3b^3A+2B^2e+4Be\gamma-8Ab\gamma>3b^3A+2BAb-4Ab\gamma=3b^3A+2Ab(B-2\gamma)=b^3A>0$, so $\alpha^{\mathrm{TR}}-\alpha^{\mathrm{TM}}=\frac{Ab^2\gamma(3b^3A+2B^2e+4Be\gamma-8Ab\gamma)}{(a-c)e(B(B+2\gamma))^2}>0$, thus $\alpha^{\mathrm{TR}}>\alpha^{\mathrm{TM}}$. Therefore $\alpha^{\mathrm{TR}}>\alpha^{\mathrm{TM}}>\alpha^{\mathrm{TC}}$,proposition 2 holds.

C.Proof of Proposition 3.

Since $\alpha^{\mathrm{TR}}>\alpha^{\mathrm{TM}}>\alpha^{\mathrm{TC}}$, there is $\alpha-\alpha^{\mathrm{TR}}<\alpha-\alpha^{\mathrm{TM}}<\alpha-\alpha^{\mathrm{TC}}$, which means $\frac{Ab}{B^2(a-c)e}(A\gamma-Bbe)<\frac{Ab}{(a-c)e(B+2\gamma)^2}(4A\gamma-(B+2\gamma)be)<\frac{Ab}{B^2(a-c)e}(2A\gamma-Bbe)$. According to the equations $\gamma-Bbe=0, 4A\gamma-(B+2\gamma)be=0, 2A\gamma-Bbe=0$, respectively, the only positive numbers b can be obtained, which are respectively b_1, b_2 and b_3. According to the assumptions, it is easy to get $b_1<b_2<b_3$. So when $\leq b_1, \alpha\geq\alpha^{\mathrm{TR}}>\alpha^{\mathrm{TM}}>\alpha^{\mathrm{TC}}$; when $b_1<b\leq b_2, \alpha^{\mathrm{TR}}>\alpha\geq\alpha^{\mathrm{TM}}>$

α^{TC} ; when $b_2 < b \leq b_3, \alpha^{\mathrm{TR}} > \alpha^{\mathrm{TM}} > \alpha \geq \alpha^{\mathrm{TC}}$; when $b > b_3, \alpha^{\mathrm{TR}} > \alpha^{\mathrm{TM}} > \alpha^{\mathrm{TC}} > \alpha$.

D.Proof of Proposition 4.

Since $x^{\mathrm{TC}} - x^{\mathrm{TR}} = -\frac{Ab}{2B} < 0$, $x^{\mathrm{TC}} - x^{\mathrm{TM}} = -\frac{2Ab\gamma}{B(B+2\gamma)} < 0, x^{\mathrm{TR}} - x^{\mathrm{TM}} = -\frac{b^3 A}{2B(B+2\gamma)} < 0$, so $x^{\mathrm{TC}} < x^{\mathrm{TR}} < x^{\mathrm{TM}}$ holds.

E.Proof of Proposition 5.

Since $\pi_{\mathrm{R}}^{\mathrm{TR}} - \pi_{\mathrm{R}}^{\mathrm{R}} = \frac{b^2 A^2}{8B} > 0$, $\pi_{\mathrm{R}}^{\mathrm{TM}} - \pi_{\mathrm{R}}^{\mathrm{M}} = \frac{A^2 b^2 (B+6\gamma)}{16B^2} > 0$. Therefore, $\pi_{\mathrm{R}}^{\mathrm{TR}} > \pi_{\mathrm{R}}^{\mathrm{R}}$, $\pi_{\mathrm{R}}^{\mathrm{TM}} > \pi_{\mathrm{R}}^{\mathrm{M}}$ holds. Since $\pi_{\mathrm{M}}^{\mathrm{TM}} - \pi_{\mathrm{M}}^{\mathrm{M}} = -\frac{b^2 A\left((b^2+4\gamma)A + 2be(b^2-4\gamma)\right)}{8(B+2\gamma)^2}, \pi_{\mathrm{M}}^{\mathrm{TR}} - \pi_{\mathrm{M}}^{\mathrm{R}} = -\frac{b^2 A\left((b^2+2\gamma)A + 4be(b^2-2\gamma)\right)}{16(b^2-2\gamma)^2}$, let $(b^2+4\gamma)A + 2be(b^2-4\gamma) = 0$ non-negative solution is b_4, $(b^2+2\gamma)A + 4be(b^2-2\gamma) = 0$ non-negative solution is b_5 , so when $b > b_4, \pi_{\mathrm{M}}^{\mathrm{TM}} > \pi_{\mathrm{M}}^{\mathrm{M}}$; when $b \leq b_4, \pi_{\mathrm{M}}^{\mathrm{TM}} \leq \pi_{\mathrm{M}}^{\mathrm{M}}$. When $b > b_5, \pi_{\mathrm{M}}^{\mathrm{TR}} > \pi_{\mathrm{M}}^{\mathrm{R}}$; when $b \leq b_5, \pi_{\mathrm{M}}^{\mathrm{TR}} \leq \pi_{\mathrm{M}}^{\mathrm{R}}$. $\pi^{\mathrm{TM}} - \pi^{\mathrm{M}} = -\frac{b^3 A(3ab - 3bc + b^2 e - 16e\gamma)}{16(\mathrm{B}+2\gamma)^2} = \frac{b^3 A(4(B+2\gamma)e - 3Ab)}{16(B+2\gamma)^2} > \frac{b^3 A(4Be - 3Ab)}{16(B+2\gamma)^2} > \frac{b^3 AAb}{16(B+2\gamma)^2} > 0$,so $\pi^{\mathrm{TM}} > \pi^{\mathrm{M}}$. $\pi^{\mathrm{TR}} - \pi^{\mathrm{R}} = \frac{Ab^2\left(-(b^2+2\gamma)A + 2B(a+be-c)\right)}{16B^2}$,since $2B(a+be-c) - (b^2+2\gamma)A > 0$, so $2B(a+be-c) - (b^2+2\gamma)A > 0$,so that $\pi^{\mathrm{TR}} > \pi^{\mathrm{R}}$.$\pi^{\mathrm{TC}} - \pi^{\mathrm{C}} = -\frac{b^2 A\left((b^2+2\gamma)A + 2be(b^2-2\gamma)\right)}{4B^2}$, the non-negative solution of $2be(b^2-2\gamma) = 0$ is b_6 ,so when $b > b_6, \pi^{\mathrm{TC}} > \pi^{\mathrm{C}}$; when $b \leq b_6, \pi^{\mathrm{TC}} \leq \pi^{\mathrm{C}}$.

Human Subjects Approval Statement

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Conflicts of Interest Disclosure Statement

The authors declare no conflict of interest in the authorship or publication of this work. The authors declare no sponsored financial sources for the undertaken study.

Author Declaration

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