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The Impact of U.S. Carbon Tariff on China's Exports and Welfare Based on Empirical Analysis and Game Models

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Abstract: This paper will begin by formulating an optimal tariff model between China and the U.S., leading us to an equilibrium point. From this vantage point, we will deduce the consequences of U.S. tariffs on China's exports and the ramifications of U.S. carbon tariffs on China's societal welfare. Next, we will develop an economic model considering the existing China-U.S. tariffs and their trading relationship. This model will help determine the influence of U.S. tariffs on China's export volume and societal welfare. In addition, we will compute the impact of U.S. tariffs on China's societal welfare and export to the U.S., factoring in China's carbon emissions per 100 yuan of GDP, and finally, concern the industrial impact of such carbon tariffs. Third, using two distinct game models, we would probe into the viability and possibility of the U.S. levying a carbon tariff on Chinese exports. The evolutionary game models reflect real-world scenarios, which point out that the U.S. will eventually apply a carbon tariff on China. Next, the dynamic game model considers different parties, China's government and firms, and different factors, environmental costs, and green subsidies. The model provides the circumstances in which the U.S. will levy a carbon tariff, whether China should provide a green subsidy, and whether the company should implement green production technology. Finally, we would discuss potential strategies China might adopt to navigate the challenges of the U.S. carbon tariff and examine the broader implications of such a move.

Keywords: Carbon tariff, U.S-China Trade Relationship, Empirical Model, Dynamic Game Model, Evolutionary Game Model, etc

1. Introduction

Since the onset of the first Industrial Revolution in the late eighteenth century, carbon emissions have surged from a mere 10 million metric tons per decade to over 37 billion metric tons by the end of 2021. Most nations have endorsed the Carbon Border Adjustment Mechanisms (CBAM) in response to rapid technological and environmental changes. This initiative seeks to deter carbon-intensive imports and encourage domestic industries to adopt greener alternatives. Numerous related carbon tariff policies also aim to curtail carbon emissions. Nonetheless, effectively reducing or eliminating these emissions remains a formidable challenge, and such tariffs can profoundly affect all stakeholders involved. The inception of these tariffs has been driven by developed countries seeking to counteract 'carbon leakage,' the phenomenon of relocating carbon-intensive industries to countries with less stringent environmental regulations.

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In recent years, China's economy has experienced rapid growth, becoming the second-largest economy in the world. Also, as the world's leading emitter of greenhouse gases, China finds herself at the epicenter of this policy shift. This growth has started to challenge the economic standing of the United States, which has been looking for ways to contain China's economic development. One key factor is that China has become the world's leading carbon emitter with its fast economic expansion. The United States has noted this and proposed carbon tariffs on China and other developing countries such as Brazil and India. [1] [2]

The U.S. Congress has already passed legislation to start applying carbon tariffs on goods imported from China since 2020. However, because of the economic downturn brought on by the pandemic, the enforcement of these carbon tariffs has not yet started. The U.S. has delayed the plan and needs to collect these tariffs, but the issue is still being examined. Hence, this paper seeks to deliberate on the impacts and potential strategies in response.

Multiple kinds of game models and estimation techniques are currently being developed. This article will provide an empirical data analysis based on China and the U.S.'s trade conditions since 2000 with a carbon tariff-welfare model to estimate the relationship between the U.S. carbon tariff and China's exports and welfare. Another major part includes two independent game models explaining the trend and viability for the U.S. to impose such a tariff and China's further strategy considerations. This leads to the conclusion that the U.S. will eventually adopt such a carbon tariff policy under the right circumstances. Possible policy recommendations for China are also provided at the end of the article.

2. Literature Review

The subject of carbon restriction has garnered immense focus in recent years. We will delve into the topic and pertinent keywords in the following manner:

Carbon tariffs, perceived as an instrument to mitigate carbon leakage, have captured significant interest. Cosbey et al. explored the intricacies of carbon tariffs, underscoring their crucial role in tackling the global climate problem. [3] These tariffs aim to dissuade carbon-intensive imports, simultaneously promoting the transition towards eco-friendlier domestic industries. This insinuates that carbon tariffs can be potent economic levers in environmental policymaking, swaying local and global attitudes towards carbon emissions.

Frankel and Rose articulated that although heightened trade exacerbates environmental challenges and augments pollution, it can paradoxically pave the way for solutions, facilitating the proliferation of green technologies and inducing economic growth geared towards environmental conservation. [4] Their research offers a foundational perspective on carbon tariffs, elucidating the imperative for such economic tools in moderating the environmental repercussions of trade.

An upcoming academic work by Monjon and Quirion probes into the issue of carbon leakage within the European Union's Emission Trading System (EU ETS). They argue that in the absence of a robust carbon tariff system, emission cutbacks in the EU might inadvertently prompt increases elsewhere, a consequence of production shifts—a dynamic termed carbon leakage. [5] Their insights amplify the pivotal role of carbon tariffs in global initiatives to curtail emissions.

From a practical point of view, Cosbey et al. furnish guidelines on the execution of border carbon adjustments — a notion intrinsically linked to carbon tariffs. Their guide covers the justification behind these adjustments and the requisite actions for their rollout. They accentuate the crucial task of aligning World Trade Organization mandates with climate objectives. [6] This research lays out a structured blueprint for the judicious implementation of carbon tariffs, ensuring they are congruent with legal and ecological benchmarks.

Given their prominent positions as top global emitters, both the US and China have dominated the literature surrounding carbon tariffs. Mattoo et al. analyzed the ramifications of carbon tariffs on

China and found that such policies could significantly impact China's export-oriented economy. [7] Meanwhile, studies focusing on the United States, such as those by Fischer and Fox, have underscored these tariffs' economic and political implications, especially within the intricate trading nexus between the US and China. [8]

Various studies have adopted a game theory [perspective] on carbon tariffs. Eichner and Pethig applied a game-theoretic model to dissect potential global reactions to carbon tariff enforcement. Their findings alluded to the possibility of a 'trade war' scenario; however, they concurrently observed that tariffs might catalyze more collaborative stances on emission reductions. Complementing this work, Branger and Quirion conduct a meta-analysis, affirming that carbon tariffs could act as an effective bulwark against carbon leakage, reiterating the significance of economic strategies in mitigating climate change. [9]

In the shadow of the COVID-19 pandemic and its ensuing global economic repercussions, a new stream of research delves into the confluence of carbon tariffs and sustainable resurgence. Hepburn et al. proposed that carbon tariffs might anchor a "green" economic revival, fostering sustainable momentum while buffering against impending climate perils. [10]

On the other side, several Chinese economists and graduate researchers also studied the effects of carbon tariffs on China and the U.S.'s benefits. Zhang Yan, in his 2012 research, postulated that in the near term, U.S.-levied carbon tariffs on China's carbon-intensive goods could dampen both the price and volume of these exports to the U.S. This is attributed to escalating production costs and waning demand, culminating in a curtailed Sino-American trade turnover. [11] He also advocates for a mutual ramp-up in avant-garde technologies and a pivot towards a low-carbon economic blueprint. Specifically for China, the imperatives of broadening domestic consumption, channelling investments into green sectors, and proactively shaping carbon tariff policies are paramount for governmental cognizance.

Another paper by Dong Xu investigated the impact of the China-U.S. carbon tariff on the balance of trade based on the CGE model. The researcher distilled two overarching implications from the carbon tariff policy: firstly, a contraction in the export volume of the tariffed sectors, and secondly, encouraging exports from non-tariffed industries. [12] Xu also broached the potential carbon emission trading framework to attain emission cutback targets, forwarding a suite of measures aptly tailored for both emerging nations, epitomized by China, and established economies, exemplified by the U.S.

Similarly, the book "The Research on the Impact of Carbon Tariffs on Agricultural Trade Based on the CGE Model" by Guo Qing developed an analysis of the current status of agricultural trade and a theoretical exploration of the impact of carbon tariffs on agricultural trade under the global emission reduction context. This book primarily employs a CGE (Computable General Equilibrium) model to quantitatively simulate the effects of carbon tariffs on global and Chinese agricultural trade. The book focuses on how carbon tariffs affect agricultural trade in the world and China within the global emission reduction framework and provides theoretical and empirical insights into this topic. [13]

In 2015, Ji Yuanyin used the GTAP model to simulate the effect of the US policy of imposing carbon tariffs on importing high-carbon emission products, with a keen focus on Sino-American trade dynamics. [14] The research results underscore that such U.S. tariffs, when imposed on high carbon footprint sectors, invariably inflate domestic prices of imported commodities, crimping the import tally but simultaneously bolstering societal welfare, albeit with a modicum uptick in the trade equilibrium. Another simulated model by Jiang Dan in 2016 showed that, under a uniform domestic carbon tax regime between China and the U.S., China's enforcement of a carbon tariff needs to be equipped to evade the ramifications of a U.S. counterpart. [15] However, in scenarios marked by divergent carbon tax landscapes across the two nations, China's proactive carbon taxation stance becomes adept at neutralizing U.S. carbon tariff pressure.

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Another study by Yan Xiaoming [16] introduced two more variables to the relationship between carbon tariff and export quantity: the trade condition and degree of trade openness. The innovative part of this paper is the introduction of two more perspectives to view the problem of trade relationship and carbon tariff, meanwhile using the Johnson-integration test and Granger causality test to enhance the results.

Comprehensively, a book in 2015, The Theoretical Mechanism of Carbon Tariffs and Their Impact on China, by Tian MingHua, takes further concern to the impact of carbon tariffs on China's national economy and national income.[17] Furthermore, "Carbon-Neutral Economics: Macroeconomic and Industry Trends Under New Constraints" by the CICC Research Institute in 2021 provides another perspective on green energy and technology advancement from manufacturing to city life, introducing the economics under the new carbon emission pattern. [18]

As inferred from prior research, the outcomes stemming from carbon tariffs implemented by China and the U.S. exhibit a spectrum of variations. Yet, a recurring theme across these studies suggests that, typically, carbon tariffs induce a slump in export volumes in the immediate aftermath. Conversely, their influence on societal welfare oscillates, contingent on the economic response mechanisms operational within the respective nations. Historically, the actual implementation of carbon tariffs has been sporadic.[19] With the unexpected onset of the pandemic and ensuing economic contractions, the U.S. seems less inclined to introduce such tariffs in its commerce with China. Nonetheless, the ramifications of carbon tariffs on societal well-being warrant scrutiny —a research question we will continue to examine in this paper.

3. Carbon Tariff Model

3.1. Introduction

When discussing the impact of the U.S.'s carbon tariff on China, two factors are unneglectable: its impact on the quantity of exports and China's social welfare. This model considers the Nash Equilibrium under the condition, and through which we finally calculated the relationship between carbon tariff, China's quantity exported, and its social welfare. Since this is a simplistic model to reveal the relationship, we do not consider the environmental cost. However, later in the dynamic game model, we considered many more factors, such as green-technology subsidies and environmental costs. Let's get into this model.

3.2. Model Set-Up

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In this model, we include China and the U.S., which we denote as countries A and B, respectively. Each country has only one firm, denoted as A and B, which produces the same product, and the product is both consumed domestically and exported to the other country. Here, we use Q_D and Q_E to represent the quantity of products sold domestically and exported, respectively. Thus, we may get the total consumption in China and the U.S. as follows:

$$Q_A = Q_{AD} + Q_{BE} \tag{1}$$

$$Q_B = Q_{BD} + Q_{AE} \tag{2}$$

We also assume an identical linear demand curve for each country's consumers, which is:

$$P = k - Q \tag{3}$$

Where k is a constant.

The cost functions for the firms are dependent only on the marginal cost c, the quantity produced, and the carbon tariff t. We assume $k > c$ for all quantities in order to reach an economics of scale during production.

3.3. Model Analysis

Now, we may start by calculating the maximized profit π_A, π_B for both companies and the quantity that reaches the maximization.

$$\pi_A(Q_{AD}, Q_{AE}) = Q_{AD}(k - Q_{AD} - Q_{BE} - c) + Q_{AE}(k - Q_{AE} - Q_{BD} - c) \tag{4}$$

$$\pi_B(Q_{BD}, Q_{BE}) = Q_{BD}(k - Q_{BD} - Q_{AE} - c) + Q_{BE}(k - Q_{BE} - Q_{AD} - c) \tag{5}$$

By differentiating both functions with respect to their variables, we can get the best response function as:

$$k - c = 2Q_{AD} + Q_{BE} \tag{6}$$

$$k - c = 2Q_{AE} + Q_{BD} \tag{7}$$

$$k - c = 2Q_{BD} + Q_{AE} \tag{8}$$

$$k - c = 2Q_{BE} + Q_{AD} \tag{9}$$

By solving the equation set, we can get the optimal quantity as:

$$Q_{AD} = Q_{AE} = Q_{BD} = Q_{BE} = \frac{k-c}{3} \tag{10}$$

The above calculations are from the company's perspective; now we can start calculating at the nation's level, which has a goal to maximize total welfare. The total welfare of each nation is composed of two parts: consumer surplus and the company's profit. According to classical economists, the consumer surplus of a market with a linear demand curve $P = k - Q$ is $\frac{1}{2}Q^2$.

Thus, we may get the social welfare function as:

$$W_A = \frac{1}{2}{Q_A}^2 + \pi_A \tag{11}$$

$$W_B = \frac{1}{2}{Q_B}^2 + \pi_B \tag{12}$$

Then, by replacing the quantities will element a and c as we calculated before, we can transform the equations into:

$$W_A = W_B = \frac{4(k-c)^2}{9} \tag{13}$$

In conclusion, currently, without the intervention of carbon tariffs, the social welfare and quantity produced are the same for both China and the U.S.

Next, we will start analyzing the case in which a carbon tariff is involved. As we mentioned before, we represent carbon tariff as t, So when the U.S. levies a carbon tariff on China's exports, China receives a carbon tariff of amount $t_B Q_{AE}$. Since the problem of optimal carbon tariff is symmetrical, China may also respond with a carbon tariff to the U.S.'s exports, which is $t_A Q_{BE}$.

The profit functions after the imposition of the carbon tariff are largely the same as the precisely calculated one, except that the profit from the exported goods should be subtracted by a carbon tariff, as:

$$\pi_A(Q_{AD}, Q_{AE}, t_B) = Q_{AD}(k - Q_{AD} - Q_{BE} - c) + Q_{AE}(k - Q_{AE} - Q_{BD} - c - t_B) \quad (14)$$

$$\pi_B(Q_{BD}, Q_{BE}, t_A) = Q_{BD}(k - Q_{BD} - Q_{AE} - c) + Q_{BE}(k - Q_{BE} - Q_{AD} - c - t_A) \quad (15)$$

Thus, we can deduce the new best response function from the first-order condition, as:

$$Q_{AE} = \frac{k-c+2t_B}{3} \quad (16)$$

$$Q_{BE} = \frac{k-c+2t_A}{3} \quad (17)$$

Meanwhile, when both countries receive a carbon tariff revenue, they will encourage their company to produce and sell domestically, which results in:

$$Q_{AD} = \frac{k-c+t_A}{3} \quad (18)$$

$$Q_{BD} = \frac{k-c+t_B}{3} \quad (19)$$

Thus, after the U.S has levied a carbon tariff on China, China's production for exports will decrease from $\frac{k-c}{3}$ to $\frac{k-c+2t_B}{3}$, meanwhile, China's production for domestic sales will increase from $\frac{k-c}{3}$ to $\frac{k-c+t_A}{3}$. The condition is the same for the U.S.

Then, given the above conditions, we can calculate the amount of social welfare for each country, which is composed of the following parts: the consumer surplus, the company's profit after the carbon tariff, and the revenue from the carbon tariff.

$$W_A = \frac{1}{2}{Q_A}^2 + \pi_A + t_A Q_{BE} \quad (20)$$

$$W_B = \frac{1}{2}{Q_B}^2 + \pi_B + t_B Q_{AE} \quad (21)$$

Since the current situation is China facing a potential imposition of the U.S.'s carbon tariff on our exported goods, this passage would only consider the case of China's social welfare.

The optimal rate of t_B, according to the maximum value of the social welfare function W_B, is the first order derivative of W_B, $\frac{k-c}{3}$.

After we substitute the carbon tariff rate into the welfare function, and then find the value of Q_{AE}, Q_{AD} that maximized the welfare function W_A in the first order condition, we can get:

$$Q_{AE} = \frac{k-c}{9} \quad (22)$$

$$Q_{AD} = \frac{4(k-c)}{9} \tag{23}$$

From this we get that the amount of export will be one-fourth of the domestic quantity sold.

Finally, we can get the relationship between W_A and the quantity exported by China, Q_{AE} , by differentiating the function W_A with respect to the carbon tariff rate t_B, through which we obtain $\frac{dW_A}{dt_B}$.

As we calculated before, W_A is composed of the domestic consumer surplus, company A's profit, and the carbon tariff levied. After substituting variables in the original function with k, c, Q_{AD}, Q_{AE}, we can get:

$$W_A = kQ_{AE} - Q_{AE}^2 - Q_{BD}Q_{AE} - cQ_{AD} - cQ_{BE} - t_BQ_{AE} \tag{24}$$

Thus, we can calculate the derivative:

$$\frac{dW_A}{dt_B} = -\frac{2}{3}k + \frac{2}{3}Q_{BD} + \frac{2}{3}c + \frac{2}{3}t_B \tag{25}$$

After simplifying the equation, we get:

$$\frac{dW_A}{dt_B} = -\frac{2(k-Q_{BD}-c-t_B)}{3} \tag{26}$$

Substituting $Q_{BD}$with equation 19, we can get

$$\frac{dW_A}{dt_B} = -\frac{2\left(k-\frac{k-c+t_B}{3}-c-t_B\right)}{3} = -\frac{2}{3}[\frac{2}{3}(k-c-2t_B)] \tag{27}$$

Substituting $Q_{AE}$with equation 16, we can get

$$\frac{dW_A}{dt_B} = -\frac{3}{4}Q_{AE} \tag{28}$$

In conclusion, from this model, we can see that with the increase of the U.S's carbon tariff t_B, China's quantity exported Q_{AE} will decrease by $-\frac{3}{4}Q_{AE}$. And with respect to the carbon tariff rate, the impact on China's social welfare is greater than the impact on the quantity exported by $\frac{4}{3}$ times

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4. Empirical Model Analysis

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4.1. Section Titles Model and Data Description

Although it is hard to get abundant empirical data for model construction, carbon tariffs are essentially the same as a normal tariff. Therefore, the relevant impact of carbon tariffs can be obtained by a tariff-and-export model.

In this section, I will create three models about the relationship between the mean tariff value that the U.S. imposed on China's exported goods (%), China's exports to the U.S. (dollar), and TRA---the total amount of trade surplus of a country in a given period of time, which reflects the trade condition of a country---from 2000 to 2020. [20] Given the pronounced disruptions brought about by the COVID-19 pandemic on global trade, data from the years 2021, 2022, and 2023 are excluded from the modeling process.

4.2. ADF Stability Test

Table 1: ADF Stability Test table

	Test statistics	**p-value**	**1% value**	**5% value**	**10% value**	**Stability test**
d.lnEx	-2.616	0.0898	-3.750	-3.000	-2.630	failed
d.lnTariff	-2.681	0.0774	-3.750	-3.000	-2.630	failed
d.lnTRA	-2.674	0.0786	-3.750	-3.000	-2.630	failed
d2.lnEx	-5.579	0.0000	-3.750	-3.000	-2.630	passed
d2.lnTariff	-5.595	0.0000	-3.750	-3.000	-2.630	passed
d2.lnTRA	-4.743	0.0001	-3.750	-3.000	-2.630	passed

The table above shows the results of the ADF stability test. Specifically, when the test statistics are smaller than all three thresholds (1% value, 5% value, 10% value) and have a significant p-value, the statistics pass the stability test.

The ADF Stability test of the data set showed that only a second-order of difference is stable through time, which allows us to further complete the co-integration model and the error correction model.

4.3. Co-integrating regression

In the following illustrations, the natural logarithm of the mean tariff rates imposed by the U.S. on China is represented as *lnTariff,* the natural logarithm of

China's exports to the U.S. are denoted as *lnEx*, the natural logarithm of China's TRA is denoted as *lnTRA*. Using data from 2000 to 2020, we created the following co-integrating regression; the outputs are below.

$$lnEx = -3.050503 * lnTariff + 0.541666 * lnTRA - 6.178735 \tag{29}$$

Table 2: Co-integrating Regression Results

lnEx	**Coefficient**	**Standard Error**	**t**	**P >|t|**	**95% Confidence Interval**
lnTariff	-3.050503	1.765474	-1.73	0.105	[-6.813522, 0.712515]
lnTRA	0.541666	0.0569879	9.50	0.000	[0.4201993, 0.6631328]
constant	-6.178735	5.503678	-1.12	0.279	[-17.90955, 5.552078]

The co-integration analysis finds the long-term relationship between lnEx and lnTariff. From the equation, we can see that the export quantity and tariff rate are inversely related: As the tariff rate from the United States increased by 1%, Chinese export quantity decreased by 3.050503%.

4.4. Error Correction Model

The co-integration analysis above certainly has some shortcomings, for example, it can only predict the long-run relationship and trend of the variables. However, when it comes to a short-run measurement, the co-integration model would be ineffective. Under this condition, an Error Correction Model (ECM) would be necessary.

Error correction models are significant in the study of time-series data, particularly when focusing on short-term dynamics. Unlike co-integration models, which are primarily preoccupied with long-run equilibria between variables, ECM enables researchers to simultaneously model both long-term and short-term fluctuations. For instance, there might be many short-term fluctuations, such as a natural disaster, a financial crisis, or even the pandemic. These short-run incidences might affect data, especially economic data by a large amount, causing the model to be inaccurate. However, using a long-term ECM reduces these impacts. Furthermore, by incorporating an error-correction term, the model allows for deviations from equilibrium to be systematically corrected over time, providing a dynamic framework for understanding both adjustment speed and direction.

Thus, we have the error correction model below:

$$dlnEx = -3.050506 * lnTariff - 0.541666 * dlnTRA - 7.41 * 10^{-7} * dlnEx^{(-1)}$$

$$+7.66 * 10^{-6} * lnTariff^{(-1)} + 1.73 * 10^{-7} - ECM^{(-1)} + 7.18 * 10^{-7} \tag{30}$$

This model states that, in the short term, for every one percentage increase in the average U.S. tariff rate to China, China's exports to the U.S. will drop by 3.050506%. The error correction coefficient is negative, which is consistent with the reverse correction mechanism.

4.5. Estimation of the impact of $30/60 carbon tariff on Chinese export and welfare

While the U.S.'s Clean Energy Security Act mandates restrictions on foreign products that fail to meet carbon emission standards starting from 2020, the actual implementation of carbon tariffs has yet to commence. Given the absence of a global precedent for carbon tariffs, precise tariff rates remain undefined.

However, by evaluating current carbon tariff benchmarks set by countries like Denmark, Finland, and Sweden, and considering international standards on carbon-tariff values, we can project that the potential carbon tariff that the U.S. might impose on China could range from $20 to $60. Accordingly, this paper will estimate the repercussions of $30 and $60 carbon tariffs on China and will delineate a function describing the interplay between the tariff and China's economic landscape.

To mitigate potential distortions due to the COVID-19 disruptions in 2020, this analysis will draw from 2019 data.

Table 3: Relevant Data of GDP and Carbon Emission

Year	GDP (China, in million $)	Carbon Emission (ton)	Carbon Emission (Ton per $ Million GDP)	Export (in million $)	Carbon Emission on exports (ton)
2019	14329710	979476	683.52814	41.84130	28599.70589

[21] [22]

From the table above, we can deduce the impact of 30/60$ carbon tariff on China's export quantity and societal welfare.

Table 4: The impact of $30/60 carbon tariff on Chinese exports and welfare

	Carbon Tariff ($)	**Tariff amount (%)**	**Decrease in export**	**Decrease in welfare**
$30 per ton	857991.1767	2.05058	6.25530%	8.34040%
$60 per ton	1715982.3534	4.10117	12.51063%	16.68084%
$*N* per ton	28599.70589**N*=*M*	*M* / 41841301 = *Q*	3.050503 * *Q*	4.067337 * *Q*

By dividing the total export amount by the carbon tariff, we can get the amount of tariff in percentage. Using the function we calculated before, every 1% increase in tariff will cause 3.050503% decrease in China's export to the U.S., so we can get the amount of declined export by multiplying the tariff amount by 3.050503. Similarly, since we deduced that every 1% decrease in exports will cause 4/3 % decrease in China's social welfare, we can get the decline of social welfare as in the table.

4.6. Industrial Analysis of the Impact of Carbon Tariff

Upon analyzing the impact of Carbon Tariffs, we have to mention that China's vast industrial landscape is not homogenous in terms of carbon emissions. Not all sectors are created equal regarding greenhouse gas emissions. Predominant emitters encompass industries such as steel, cement, and coal mining. These sectors are inherently carbon-intensive, given their dependence on fossil fuels and energy-dense operations. The advent of a carbon tariff poses a more pronounced threat to these industries, as they might incur steeper charges, potentially diminishing the competitiveness of their exports in the U.S. market. [23]

Conversely, industries marked by lower emission levels—like electronics, textiles, or specific segments of light manufacturing—might experience a softer blow. Their modest carbon footprints suggest that they would be subjected to relatively minor cost surges when exporting to the U.S.

Given these variances, a sector-specific examination of the carbon tariff's impact is imperative. This article will delve into this analysis using the subsequent methodology:

First, we assume the export amount of each industry to be 1 million dollars. Then, according to DongXu's paper, a carbon emission index for each industry can be deduced by dividing the gross domestic industrial product by the carbon emission amount. [12] Next, the carbon emission amount that the corresponding industry produced for the products they export to the U.S. can be calculated. Finally, we would deduce the percentage of carbon tariff with a standard of $30 per ton of carbon emission. The table is below.

Table 5: The Impact of Carbon Tariffs on Different Industrial

	High/low carbon Emission	**Carbon Emission Index**	**Carbon Emission (ton)**	**Estimated Carbon Tariff ($)**	**Percentage of Carbon Tariff**
Construction materials	High	0.1383	1,383	41,490	4.419%
Petrochemical	High	0.0326	326	9,780	0.978%
Electronic information	Low	0.0022	22	660	0.066%
Machinery	Low	0.0059	59	1,770	0.177%

From the above chart, we can see that the high-carbon emission industries such as construction materials are largely affected by the carbon tariff policy.

4.7. Empirical Model Summary

Despite being rooted in environmental considerations, carbon tariffs operate in a manner that mirrors traditional tariffs. Therefore, to explore their intricate implications, we employed a tariff-and-export model. Spanning from 2000 to 2020, I constructed three distinct models. Due to the unprecedented turbulence caused by the COVID-19 pandemic in global trade, we consciously excluded data from 2021 to 2023. [24] This decision ensures that the anomalies introduced during these years don't bias the analysis. To affirm the stability and reliability of my datasets, we subjected them to the Augmented Dickey-Fuller (ADF) test. The results had to meet specific thresholds: they must lie below the 1%, 5%, and 10% levels. Moreover, the p-value, indicative of the statistical significance, was rigorously scrutinized.

Following this, we orchestrated both a co-integration and error correction models, reflecting the short- and long-term relationship between carbon tariffs, quantity exported, and the TRA. These were designed to estimate the implications of imposing a carbon tariff of $30 or $60 per ton on China, dissecting the national and industrial consequences. From the perspective of international trade, an increase in the tariff rate is bound to lead to a reduction in bilateral trade volumes, adversely affecting the social welfare of both countries. From the perspective of social welfare, introducing a carbon tariff invariably curtails the welfare of the exporting country. The magnitude of this welfare reduction is directly proportional to the tariff rate levied. A persistent negative equilibrium characterizes the relationship between China's exports to the US and the import tariff rate imposed by the US. It's reasonable to surmise that carbon tariffs will profoundly dampen a country's export capabilities. Specifically, under the proposed carbon tariff rates of $30 or $60, China's trade exports are projected to dip by 6.25530%, translating to an 8.34040% decline in China's social welfare. Finally, we demonstrated an industrial analysis of the carbon tariff, concluding that the carbon tariff will harm the high-emission industries by a much more significant magnitude.

5. Evolutionary Game Model

5.1. Introduction

The origins of evolutionary game theory can be traced back to the 1960s when ecologists discovered a striking similarity between the results of animal and plant evolution based on the principles of "survival of the fittest" and the Nash equilibrium in game theory. Evolutionary game theory was formally born in the 1970s at the hands of ecologists Smith and Price, marked by their joint proposal of the Evolutionary Stable Strategy (ESS).

Over time, as the limitations of classical game theory and neoclassical economics emerged, the stage was set for evolutionary game theory's rise. Its establishment as a distinct academic discipline in economics occurred during a 1992 conference at Cornell University. Since then, its influence in economics has grown, positioning it at the discipline's vanguard. [25]

5.2. Model Set Up

In this model, we have two countries: China and U.S.

Table 6: Matrix of Evolutionary Game Model

		U.S. Not Levy	U.S. Levy
China	Not Accept	P, Q	-R, 0
	Accept	P, Q	P-a, Q+b

Now, we will introduce the matrix specifically. In the first case, the relationship remains the same when China disagrees with the United States' carbon tariff advocation and the U.S. does not advocate a carbon tariff on China's exports. China will earn a revenue of amount P, and the U.S. will earn an income of Q through trade. In the second case, the relationship does not change when China agrees with the United States' carbon tariff advocation. Still, the U.S. does not advocate a carbon tariff on China's exports. China will earn a revenue of P, and the U.S. will earn a revenue of Q through trade. In the third case, the relationship would change when China disagrees with the United States' carbon tariff advocation, but the U.S. insists on advocating a carbon tariff on China's exports. China would stop exporting products with high carbon emission rates to avoid the carbon tariff. In this case, China would lose a portion of R revenues because they cannot ship those products, while the U.S. cannot earn anything since China stopped exporting to them. So, we get the combination (-R, 0).

Lastly, when China accepts the U.S.'s tariff and the U.S. levies them, China will lose a part of its revenue because of the rising cost of exporting products, denoted as *a*, and the U.S. will earn a corresponding amount, designated as *b*. In this case, the combination will be (P-a, Q+b).

Next, we may start analyzing the model using evolutionary game theory.

5.3. Model Analysis

Since we assume both countries conform to the boundary rationality assumption, we set the probability that China does not accept the carbon tariff as x, then the probability that China accepts the carbon tariff is 1-x. Similarly, the probability that U.S does not levy the carbon tariff as y, then the probability that U.S levies the carbon tariff is 1-y. $(0 \leq x \leq 1, 0 \leq y \leq 1)$

From the matrix above, we can deduce the replicated dynamic equation:

For China, the expected utility of not accepting the carbon tariff is:

$$U_1 = P * y + (-R) * (1 - y) \tag{31}$$

The expected utility of accepting the carbon tariff is:

$$U_2 = P * y + (P - a) * (1 - y) \tag{32}$$

The mean expected utility is:

$$U = U_1 * x + U_2 * (1 - x) \tag{33}$$

The replicated dynamic equation for China if they don't accept the carbon tariff is:

$$F(x) = \frac{dx}{dt} = (U_1 - U) * x \tag{34}$$

After replacing U_1, U in the equation, we get:

$$F(x) = \frac{dx}{dt} = x(1 - x)(1 - y)(a - P - R) \tag{35}$$

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According to our assumption, $P - a > 0, R > 0$, so $(a - P - R) < 0$.
When $y = 1$, for any value of x, the equation equals 0, which is stable.
When $y < 1$, let $F(x) = 0$, x can be either 0 or 1.
Now we find the derivative of F(x) with respect to x, and get:

$$\frac{dF(x)}{dx} = (1 - 2x)(1 - y)(a - P - R) \tag{36}$$

After replacing x with 0, we get:

$$\frac{dF(x)}{dx} = (1 - y)(a - P - R) \tag{37}$$

Since $(1 - y) > 0, (a - P - R) < 0, \frac{dF(x)}{dx} < 0$. This indicates that x=0 is stable and is the evolutionary equilibrium solution.
After replacing x with 1, we get:

$$\frac{dF(x)}{dx} = -(1 - y)(a - P - R) \tag{38}$$

Which is positive, indicating that x=1 is unstable.
According to the above results, we can draw the phase diagram as follow:

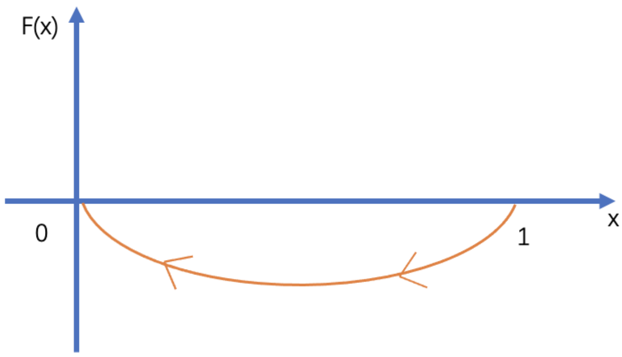

Figure 1: Phase Diagram for Evolutionary Equilibrium Solution (1)

Similarly, for U.S, the expected utility of not levying the carbon tariff is:

$$V_1 = Q * x + Q * (1 - x) = Q \tag{39}$$

The expected utility of not levying the carbon tariff is:

$$V_2 = 0 * x + (Q + b) * (1 - x) \tag{40}$$

The mean expected utility is:

$$V = V_1 * y + V_2 * (1 - y) \tag{41}$$

The replicated dynamic equation for U.S if they don't levy the carbon tariff is:

$$F(y) = \frac{dy}{dt} = (V_1 - V) * y \tag{42}$$

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After replacing V_1, V in the equation, we get:

$$F(y) = \frac{dy}{dt} = y(1-y)[x(Q+b)-b] \tag{43}$$

When $x = \frac{b}{Q+b}$, F(y) is always 0 and is stable.
When $x < \frac{b}{Q+b}$, y can be either 0 or 1.
Now we find the derivative of F(y) with respect to y, and get:

$$\frac{dF(y)}{dy} = (1-2y)[x(Q+b)-b] \tag{44}$$

After replacing y with 0, we get:

$$\frac{dF(y)}{dy} = [x(Q+b)-b] \tag{45}$$

Since $[x(Q+b)-b] < 0$, y=0 is stable and is the evolutionary equilibrium solution.
After replacing y with 1, we get:

$$\frac{dF(y)}{dy} = -[x(Q+b)-b] \tag{46}$$

Since $[x(Q+b)-b] < 0, \frac{dF(y)}{dy} > 0$, which indicates that y=1 is unstable and is not the evolutionary equilibrium solution.
Accordingly, we can get the phase diagram as follow:

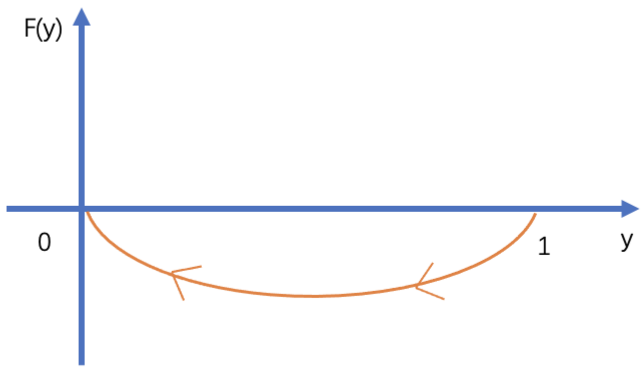

Figure 2: Phase Diagram for Evolutionary Equilibrium Solution (2)

When $x > \frac{b}{Q+b}$, opposite to the previous result, y=1 is the evolutionary equilibrium solution, but y=0 is not.
Thus, we get a phase diagram as follow:

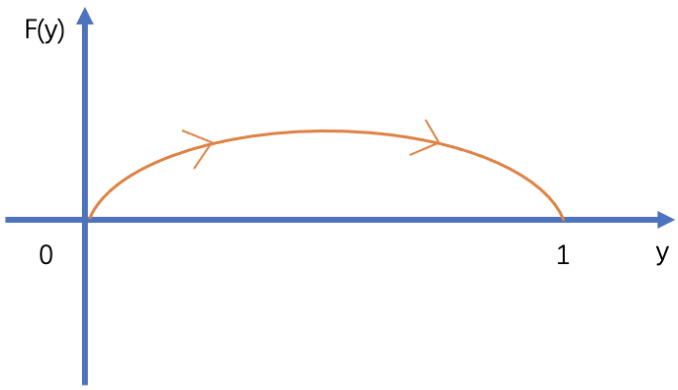

Figure 3: Phase Diagram for Evolutionary Equilibrium Solution (3)

Summing up the information above, we can get:
When $y < 1$, $x \to 0$;
When $x > \frac{b}{Q+b}$, $y \to 1$;
When $x < \frac{b}{Q+b}$, $y \to 0$;
Then we may combine the results into a single diagram as follow:

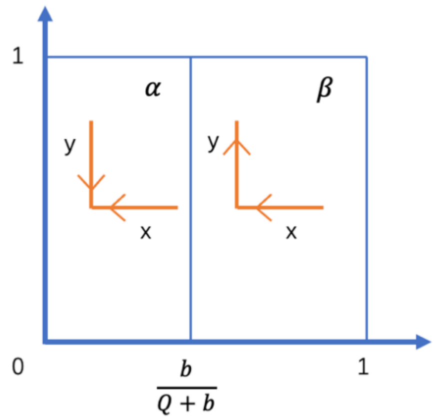

Figure 4: Evolutionary Equilibrium Solution for Both Parties

With the diagram, we can implement the dynamic analysis: when the combination falls in area α, since $x < \frac{b}{Q+b}$ and $y < 1$, the changing trend of x, y is $x \to 0$, $y \to 0$, the resulting evolutionary equilibrium solution is $x = 0, y = 0$. When the combination falls on area β, since $x > \frac{b}{Q+b}$, $y < 1$, the changing trend of x, y is $x \to 0$, $y \to 1$. However, after a period of time, when x become smaller than $\frac{b}{Q+b}$, the condition would again turn into $x < \frac{b}{Q+b}$, $y < 1$, leading to the changing trend $x \to 0$, $y \to 0$ and the resulting evolutionary equilibrium solution $x = 0, y = 0$.

In summation, utilizing the framework of evolutionary game theory and operating under "bounded rationality," we can analyze the impact of carbon tariffs on China-US trade dynamics. The evolutionary equilibrium results for both nations under this model are x=0 and y=0. Over time, this equilibrium suggests China's inclination towards accepting the tariff grows, moving away from the probability of rejection. Similarly, the U.S. displays a mounting likelihood of implementing the tariff, distancing itself from the probability of abstention. As such, the evolutionarily stable strategy for both nations concerning carbon tariffs resolves to (accept levying). Thus, the evolutionary game theory implies that as time advances, China will likely lean towards a conciliatory approach, accepting U.S.-imposed carbon tariffs on its high-carbon products. Conversely, the U.S. will gravitate towards the execution of these tariffs on China's high-carbon exports.

5.4. Current Situation Analysis

While the U.S. has been discussing the implementation of a carbon tariff on China since as early as 2019, such a tariff has yet to be levied. What could be the reasons behind this delay?

Firstly, the global pandemic that began in 2020 adversely affected the economic growth of both the U.S. and China, leading to a delay in tariff implementation. By the end of 2022, the ramifications of the pandemic persisted, preventing both nations from reconsidering the proposal.

Secondly, the onset of 2022 saw the U.S. grappling with a high inflation crisis, further delaying its recovery from the pandemic. Implementing carbon tariff policies during this period could have exacerbated tensions in the China-U.S. trade relationship, potentially deepening the U.S. economic challenges and pushing inflation rates even higher.

In conclusion, the circumstances outlined above have necessitated the U.S. to delay its plans to introduce carbon tariffs on China. Yet, as projected by the evolutionary model, it seems inevitable that the U.S. will eventually implement such tariffs, driven either by environmental concerns or strategic economic considerations vis-à-vis China.

As our analysis concludes, new questions emerge: When might the U.S. decide to levy a carbon tariff on China? Under what conditions would China introduce green subsidies for its enterprises? And what factors would prompt Chinese companies to adopt eco-friendly production methods? The ensuing dynamic game model, which analyzes the interactions between the U.S., China, and Chinese businesses, aims to illuminate these queries.

6. Dynamic Game Model

6.1. Introduction

In the last part we determined that over time, the evolutionary model suggests the U.S. is likely to impose carbon tariffs on China's exports. We also raised a question about the condition under which three key stakeholders – the U.S., China, and companies – would make their respective decisions.

In this section, we introduce a three-stage dynamic game model with complete information. This model will explore the scenarios under which developed countries might impose carbon taxes, developing countries might adopt green subsidy policies, and businesses in developing countries might transition to low-carbon technologies in their production processes. [26]

6.2. Model Set-Up

In this model, we introduce two game parties, or two countries: China, the developing country, and the U.S., the developed country. Each has one domestic company that produces homogeneous products (Also denoted as Company A for China, and Company B for the U.S.). We assume that the only market for the product is the U.S., which means that China will have to export the goods to the U.S.

The total cost for the companies would be $\frac{kQ^2}{2}$, where Q is the quantity of production, and k is a constant. The lower the cost of production, the greater the trade surplus for a company will be.

When both companies sell their products to the U.S. market with price P, if we assume the utility function for consumers to be:

$$U = Q_A + Q_B - \frac{(Q_A+Q_B)^2}{2} \tag{47}$$

Then we may deduce the price from the inverse demand function for the U.S., which would be:

$$P = 1 - (Q_A + Q_B) \tag{48}$$

Thus, by subtracting P from U, we can get the consumer surplus as:

$$CS = \frac{(Q_A+Q_B)^2}{2} \tag{49}$$

Carbon emission is inevitably a problem during production, so we assume a carbon emission rate per unit product of e, where e is a constant. The smaller the emission rate, the greater the carbon emission advantage a company will have. We assume every unit of carbon emission causes damage of amount λ to the environment. So the amount of environmental damage caused by enterprise A will be:

$$\lambda e_A Q_A \tag{50}$$

The U.S then will levy a carbon tariff on China, denoted as T. Then, China will choose whether adopt a green subsidy for the company on their products, denoted as S_D, to encourage low-carbon production technologies.

Since China is a developing country, company A has lower production costs but emits more CO2 per unit of product. Specifically, we have $0 < k_A < k_B$ and $0 < e_A < e_B$. For clarity of analysis, let $k_A = k, k_B = 1, e_A = e, e_B = 1$. Thus, we have: $0 < k < 1; 0 < e < 1$.

6.3. Model Analysis

In the first stage, the U.S. choose a carbon tariff per unit of product, determining the optimal carbon tax rate T.

In the second stage, China decides whether to implement green subsidies and determine the optimal green subsidy S_A.

In the third stage, after observing the policies of both countries, company A decides whether to adopt low-carbon technologies. They also compete with company B in a Cournot competition model to determine the optimal production quantities (Q_A, Q_B).

Finally, we can reach the subgame-perfect Nash equilibrium with inverse induction and solve the three-stage game.

We can thus draw the game tree illustration:

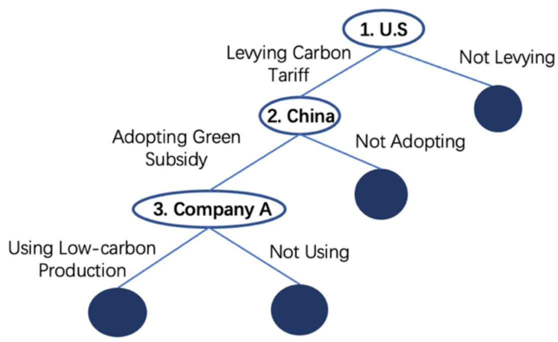

Figure 5: Game Tree Illustration

Now, we may start the calculation of the game. Since we are using backward induction, we start from phase 3, analyzing the circumstances in which the U.S. chooses not to levy the carbon tariff, levying, in which China chooses not to adopt green subsidies for companies, adopting them, and in which company A chooses to use low-carbon production, and not using them.

6.3.1. Phrase 3

First, when the U.S. chooses not to levy carbon tariffs, China and Company A will not change from their current situation. At this time, the profit function (denoted as $\pi_{A/B}$) of both companies will be composed of two parts: the sales revenue and the production cost.

The profit function for company A will be:

$$\pi_A(Q_A, Q_B) = (1 - Q_A - Q_B)Q_A - \frac{kQ_A^2}{2} \tag{51}$$

The profit function for company B will be:

$$\pi_B(Q_A, Q_B) = (1 - Q_A - Q_B)Q_B - \frac{Q_B^2}{2} \tag{52}$$

To calculate the quantity that maximizes profit value for each function, we need to calculate the first-order partial derivative. Thus, we get:

$$Q_A^i = \frac{2}{3k+5} \tag{53}$$

$$Q_B^i = \frac{1+k}{3k+5} \tag{54}$$

By replacing them with the profit function, we may get:

$$\pi_A^i = \frac{(2+k)(Q_A^i)^2}{2} \tag{55}$$

$$\pi_B^i = \frac{3(Q_B^i)^2}{2} \tag{56}$$

Second, when the U.S. chooses to levy carbon tariff as an amount of T, while China doesn't adopt a green subsidy, or company A doesn't accept the subsidy and produces with low carbon emissions, the profit function of company A will be composed of three parts: the carbon tariff, the sales revenue, and the production cost:

$$\pi_A(Q_A, Q_B, T) = (1 - Q_A - Q_B)Q_A - \frac{kQ_A^2}{2} - TQ_A \tag{57}$$

The production function of Company B remains unchanged:

$$\pi_B(Q_A, Q_B) = (1 - Q_A - Q_B)Q_B - \frac{Q_B^2}{2} \tag{58}$$

From the first-order condition, by calculating the partial derivative where $\pi_{A,B} = 0$, where the function reaches its maximum, we obtain:

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$$Q_A^{ii} = \frac{2-3T}{3k+5} \tag{59}$$

$$Q_B^{ii} = \frac{1+k+T}{3k+5} \tag{60}$$

By replacing them with the profit function, we may get:

$$\pi_A^{ii} = \frac{(2+k)(Q_A^{ii})^2}{2} \tag{61}$$

$$\pi_B^{ii} = \frac{3(Q_B^{ii})^2}{2} \tag{62}$$

By comparing the optimal output and maximum profit of both enterprises at this stage, it can be determined, under the assumptions of this paper, whether enterprise A chooses to adopt low-carbon technology for production, the optimal output and maximum profit of enterprises in both countries have been affected.

Third, when the U.S. chooses to levy carbon tariff as an amount of T, China adopts a green subsidy and company A uses low-carbon emission production, the unit cost of company A increases to k_1, where $k < k_1 < 1$. Here, the profit function of company A will be composed of four parts: the green subsidy, the carbon tariff, the sales revenue, and the production cost:

$$\pi_A(Q_A, Q_B, T, S_A) = (1 - Q_A - Q_B)Q_A - \frac{k_1 Q_A^2}{2} - TQ_A + S_A Q_A \tag{63}$$

The production function of company B remains unchanged:

$$\pi_B(Q_A, Q_B) = (1 - Q_A - Q_B)Q_B - \frac{Q_B^2}{2} \tag{64}$$

From the first-order condition, we obtain:

$$Q_A^{iii} = \frac{2-3T+3S_A}{3k_1+5} \tag{65}$$

$$Q_B^{iii} = \frac{1+k_1+T-S_A}{3k_1+5} \tag{66}$$

By replacing them with the profit function, we get:

$$\pi_A^{iii} = \frac{(1+k_1)(Q_A^{iii})^2}{2} \tag{67}$$

$$\pi_B^{iii} = \frac{3(Q_B^{iii})^2}{2} \tag{68}$$

Since $\frac{\partial(Q_A^{iii})}{\partial S_A} > 0, \frac{\partial(Q_B^{iii})}{\partial S_A} < 0$, we can see that the greater the amount of China's green subsidy (S_A), the greater the quantity produced and exported by company A (Q_A^{iii}), and the less the quantity produced and sold domestically by company B (Q_B^{iii}).

Since $\frac{\partial(Q_A^{iii})}{\partial T} < 0, \frac{\partial(Q_B^{iii})}{\partial T} > 0$, the greater the amount of the U.S's carbon tariff (T), the less the quantity produced and exported by company A (Q_A^{iii}), and the greater the quantity produced and sold domestically by company B (Q_B^{iii}).

In conclusion, the carbon tariff and the green subsidy are in an inverse relationship.

6.3.2. Phrase2

In this stage, China will decide whether to implement green subsidies based on the objective of maximizing national welfare and from this decision, determine the optimal subsidy rate.

First, if the U.S. chooses not to levy any carbon tariff on China's products, China would not propose any policies, meanwhile, the welfare function for China only includes company A's profits and environmental cost, which is e_A per unit product. Thus, when a company maximizes their profit, China's welfare was maximized. We thus have:

$$W_A^i(Q_A^i, Q_B^i) = (1 - Q_A^i - Q_B^i)Q_A^i - \frac{k(Q_A^i)^2}{2} - \lambda Q_A^i \tag{69}$$

After replacing Q_A^i, Q_B^i with their values we calculated in the previous part, we get:

$$W_A^i(Q_A^i, Q_B^i) = \frac{2[(k+2)-\lambda(3k+5)]}{(3k+5)^2} \tag{70}$$

Second, if the U.S. chooses to levy carbon tariff as an amount of T, while China doesn't adopt a green subsidy, or company A doesn't accept the subsidy and produces with low carbon emissions, the welfare function of China includes company A's profits, with the carbon tariff counted, and environmental cost, which is:

$$W_A^{ii}(Q_A^{ii}, Q_B^{ii}, S_A) = (1 - Q_A^{ii} - Q_B^{ii})Q_A^{ii} - \frac{k(Q_A^{ii})^2}{2} - TQ_A^{ii} - \lambda Q_A^{ii} \tag{71}$$

We then can simplify the function to:

$$W_A^{ii}(Q_A^{ii}, Q_B^{ii}, S_A) = \frac{(2-3T)[(2+k)(2-3T)-\lambda(3k+5)]}{2(3k+5)^2} \tag{72}$$

Third, when the U.S. chooses to levy carbon tariff as an amount of T, China adopts a green subsidy and company A uses low-carbon emission production, the unit carbon emission of company A decreases to e, and the welfare function of China includes company A's profits, with the carbon tariff counted, the green subsidy, and environmental cost, which is:

$$W_A^{iii}(Q_A^{iii}, Q_B^{iii}, S_A) = (1 - Q_A^{iii} - Q_B^{iii})Q_A^{iii} - \frac{k_1(Q_A^{iii})^2}{2} - TQ_A^{iii} - \lambda e Q_A^{iii} \tag{73}$$

From the first-order condition, we obtain:

$$S_D^{iii} = \frac{[\lambda e(3k_1+5)-2(k_1+1)]}{2(k_1+1)} \tag{74}$$

In this case, since all factors are dependent to S_D^{iii}, we can directly apply it to the parameters in the welfare function, which results in:

$$W_A^{iii} = \frac{7(\lambda e)^2}{4(k_1+1)} \tag{75}$$

6.3.3. Phrase 1

Finally, in the first stage, the U.S. will decide whether to impose a carbon tax based on the objective of maximizing national welfare. If they choose to levy a carbon tax, they will then determine the optimal carbon tax rate.

First, when the U.S. chooses not to impose a carbon tax, its social welfare function consists of four parts: sales revenue, production costs, consumer surplus, and environmental damage. In this case, the maximized profit of company B is equivalent to the maximized social welfare, which is:

$$W_B^i(Q_A^i, Q_B^i) = (1 - Q_A^i - Q_B^i)Q_B^i - \frac{(Q_B^i)^2}{2} + \frac{(Q_A^i+Q_B^i)^2}{2} - \lambda e Q_B^i \tag{76}$$

Which can be simplified to:

$$W_B^i(Q_A^i, Q_B^i) = \frac{[(c+1)(2c+4)-\lambda e(c+1)(3c+5)]}{(3c+5)^2} \tag{77}$$

Second, if the U.S. chooses to levy carbon tariff as an amount of T, while China doesn't adopt a green subsidy, or company A doesn't accept the subsidy and produces with low carbon emissions, the welfare function of the U.S. includes company B's sales revenue, tariff revenue, production costs, consumer surplus, and environmental damage, which is:

$$W_A^{ii}(Q_A^{ii}, Q_B^{ii}, T) = (1 - Q_A^{ii} - Q_B^{ii})Q_A^{ii} - \frac{(Q_A^{ii})^2}{2} - TQ_A^{ii} - \lambda e Q_A^{ii} + \frac{(Q_A^{ii}+Q_B^{ii})^2}{2} \tag{78}$$

From the first-order condition, we obtain:

$$T_D^{ii} = \frac{[-12(\lambda e(k+1))-27\lambda k-15\lambda+21k+14]}{17+18k} \tag{79}$$

In this case, similarly, since all factors are dependent to S_D^{iii}, we can directly apply it to the parameters in the welfare function, which results in:

$$W_A^{ii} = \frac{(4+3k)[\lambda(20+e-18k)]^2}{2(17+18k)} \tag{80}$$

Third, when the U.S. chooses to levy carbon tariff as an amount of T, China adopts a green subsidy and company A uses low-carbon emission production, the unit carbon emission of company A decreases to e, and the welfare function of the U.S. includes company B's sales revenue, tariff revenue, production costs, consumer surplus, and environmental damage, which is:

$$W_A^{iii}(Q_A^{iii}, Q_B^{iii}, T) = (1 - Q_A^{iii} - Q_B^{iii})Q_A^{iii} - \frac{k_1(Q_A^{iii})^2}{2} - TQ_A^{iii} - \lambda e Q_A^{iii} + \frac{(Q_A^{iii}+Q_B^{iii})^2}{2} \tag{81}$$

From the first-order condition, we obtain the optimal value for T, and we can get the welfare function as:

$$W_A^{iii} = \frac{[96\lambda e(3+k_1)(1+k_1)-(251k_1^2+502k_1+265)]}{128(k_1+1)^2} \tag{82}$$

Now, by incorporating the calculated optimal green subsidy rates and optimal carbon tax rates into the welfare functions of the two countries, we can fill the game tree for this three-stage dynamic game:

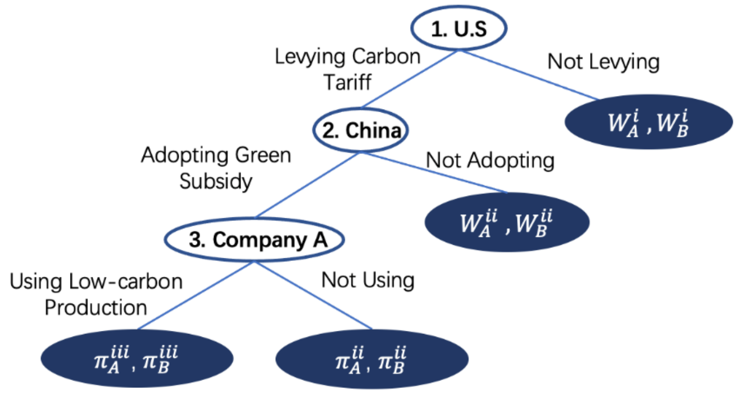

Figure 6: Game Tree Illustration with Solutions

Last but not least, by comparing each combination's value as we calculated above, we can conclude that:

When $\lambda < \frac{(3k+5)k_1}{90e}$; the U.S will choose to levy the carbon tariff in order to maximize their domestic welfare.

When $\lambda < \frac{5}{3(23+18k_1)-e)}$; China will adopt a green subsidy for company A to stimulate green development in the nation.

When $k_1 < \frac{9\lambda e^2}{9k+3ke+4e+5}$; company A will accept the subsidy and use green production technology.

6.4. Model Set-Up

In summary, this part concerns the conditions under which the U.S., China, and companies in China will adopt different strategies. The results underscore that when green subsidies from the Chinese government reach a specific threshold relative to the cost of adopting low-carbon technologies, Chinese enterprises are inclined to transition towards them. Moreover, the extent of environmental degradation plays a pivotal role in shaping the policy preferences of China and the U.S. within this strategic framework.

In practical terms, the three identified scenarios detailing the strategic choices of the involved parties offer valuable insights. These can serve as benchmarks for real-world policymaking, aiding in formulating U.S. carbon tariff policies and developing strategies to navigate these tariffs effectively.

7. Policy Recommendations

In the long run, developing countries must prioritize technological advancements and develop towards low-carbon production transformation. This strategy acts as a buffer against potential carbon tariffs from other countries and is pivotal for sustained economic growth. Paul Romer, who perceives technology as a public good with widespread benefits, posits that investing in research and development can propel a nation toward endogenous growth. [27] Such an approach steers the country towards a more stable growth trajectory and enhanced economic efficiency. Since pollution is a global challenge, addressing it becomes a collective responsibility, underscoring the need for every country to be proactive. [28]

Notably, the U.S. hasn't levied carbon tariffs on developing nations, partly due to their relatively moderate emission levels and higher production costs. In light of this, China should proactively transition to more advanced production technologies. Encouraging firms to invest in research and development requires a dual-pronged approach: internal incentives from the government and external pressures from the global community.

In addition, since the current carbon emissions come majorly from the combustion of fossil fuels such as coal and crude oil, we should also pay more attention to developing new, clean technologies such as hydroelectricity, wind electricity, solar electricity, and nuclear electricity. We should also decrease our reliance on fossil fuels, which is an inevitable task for the world since these fossil fuels are considered non-renewable energy sources. Thus, paying more attention to green, renewable sources also promotes the development of the globe.

The confrontation about carbon tariffs between developed and developing countries brings serious consequences. It can decrease their social welfare in the long run. Hence, the core objective of the carbon tariff for developed countries should be to foster a greener global production chain. This collaborative approach allows nations to break free from the prisoner's dilemma. One country can achieve a synergistic partnership by offering labor and other technology. For instance, the U.S. may provide China with its technologies, and in return, China can provide abundant labor or capital to reach a win-win stage. If benefits are distributed equitably, this alliance could yield a more advantageous balance than solely enforcing carbon tariffs.

From a domestic perspective, there are also appropriate policies to adopt. China can promote carbon emission trading between enterprises. Such institutions have already existed, such as the EU ETS of Europe and the RGGI in the U.S. [29] This exchange system aims to give low-emission companies a larger developing space, and both high-emission companies and low-emission ones can get what they need, reaching a more beneficial balance. This policy can also promote the development of greener technologies among those high-emission companies.

Another domestic strategy in the short run is to consider domestic carbon taxes or introduce carbon subsidies. According to the World Trade Organization policy, goods shouldn't be double-taxed. This allows countries like China to levy internal taxes, channelling these revenues into forward-looking projects. A compelling method for such nations to curb carbon emissions is through "carbon-neutral" policies. Though similar to carbon taxes, these policies have a direct environmental impact. Compelling carbon-intensive businesses to undertake actions like tree planting to offset their carbon footprint indirectly pushes them to adjust their product pricing to account for these additional expenditures.

In conclusion, coordinating international regulations and product standards can significantly bolster energy efficiency efforts. Such collaboration can enhance cost-effectiveness, amplify incentives for innovation, foster transparency, and boost global trade. Meanwhile, implementing domestic carbon taxes to offset the international ones or encourage carbon emission exchange systems will also assist in putting off current situations and promote low-carbon technology advancements.

8. Conclusion

Drawing from extensive empirical studies by multiple researchers and economists in the past decade, the implications of U.S. carbon tariffs on China's exports and welfare are multifaceted. Both nations need help balancing trade with carbon-neutral objectives.

As revealed in the title, this passage aims to find the impact of the U.S. carbon tariff on China's exports and welfare. Thus, the relationship between China's exports and welfare is to be found first, which is done using a dynamic game model, through which we discovered that the relationship between exports and welfare is $-\frac{4}{3}$ under ideal conditions.

Next, using data from the past two decades, a realistic result is that as the tariff rate from the United States increased by 1%, Chinese export quantity decreased by 3.050503%. Consequently, the industrial and quantitative analysis of the carbon tariff on China is done.

After the quantitative analysis of the data, it is essential to use the game model to analyze when and how the U.S. will levy a carbon tariff on China and China's potential policies to combat them. From the evolutionary game model, we conclude that China will likely lean towards accepting U.S.-imposed carbon tariffs on its high-carbon products. Conversely, the U.S. will gravitate towards the execution of these tariffs on China's high-carbon exports. While this action was delayed by the outburst of COVID-19 and the high inflation in the U.S., A more specific scenario is included in the dynamic game model, in which we estimated the circumstances under which the U.S., China, and a Chinese firm will proceed. The results show that when green subsidies from the Chinese government reach a specific threshold relative to the cost of adopting low-carbon technologies, Chinese enterprises are inclined to transition towards them. Moreover, the extent of environmental degradation plays a pivotal role in shaping the policy preferences of both China and the U.S. within this model.

In summary, there are many possibilities and circumstances under a scenario of a carbon tariff. Still, China has different tactics to counter them, such as implementing the domestic carbon tax, prioritizing technological advancements toward low-carbon production transformation, promoting carbon trade, etc.

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