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Evolutionary game analysis of forestry carbon sink trading model under blockchain technology

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ABSTRACT

As a new balanced economy, the green economy guides the upgrade and transformation of industrial structures based on the original concept of sustainable development. Reducing carbon emissions is indispensable for achieving better and faster green economic development. From a functional perspective, forestry carbon sinks have good carbon sequestration potential and have positive attributes, such as climate regulation and biodiversity maintenance, for the entire ecosystem. To promote the continuous development of forestry carbon sink trading in China, blockchain, a new technology with several advantages such as traceability, supervision, and tamper-proofness, has emerged, which creates a good market trading environment and has made a breakthrough in the trading mode. If forestry carbon sink trading is effectively supported, organic combinations and simultaneous synergistic development can be conducted, which will open new avenues for the carbon sink economy. In this study, a game model of the forest carbon sink trading mode under blockchain technology was constructed from the perspective of traders, and influential factors, such as the carbon sink available for sale by the supply side and the demand side's perspective towards emission reduction, were considered. Subsequently, the MATLAB R2020b software was used to conduct a simulation analysis of the transactions, thereby showing the evolutionary path of the game between the two sides and the influence mechanism of the addition of blockchain technology on the evolution trajectory of the demand-side decision. The findings indicate that, from the perspective of participating traders, the inclusion of blockchain technology in forestry carbon sink trading resulted in positive effects. Moreover, the greater the probability that the carbon sinks available for sale in the market can meet the demand, the more likely the demand side is to participate in the transaction.

1. Introduction

After 40 years of reform and initiation, economic growth has been considered the most significant factor affecting carbon emissions [1]. With the comprehensive transformation and continuous development of the Chinese economy and society, the Party Central Committee has attached great importance to green economic development. Green development has gradually become an important part of high-quality economic development [2], and pollution and carbon reduction have attracted considerable attention as the core tasks of green and low-carbon development. As a major response to climate change, forestry carbon sequestration is an important part

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of “dual carbon” research. Carbon offsetting is considered the most economical method and offers multiple benefits [3]. Therefore, understanding carbon peaking and carbon neutrality, studying the carbon sink economy and its trading mode, and making informed decisions are becoming difficult because of the particularity of forestry carbon sink trading links and the complexity of trading prices. To some extent, blockchain technology can compensate for the shortcomings of traditional models. Therefore, introducing blockchain into the forestry carbon sink trading mode will address certain challenges and have significant development potential. The concept of blockchain technology differs from traditional centralized transaction modes. It is essentially a decentralized distributed ledger database that can realize peer-to-peer services and avoid paying large commissions to intermediaries, thereby improving the fund utilization rate. When transmitting transaction information, it is no longer addressed but directly diffused to the entire network in a broadcast manner. However, only parties with matching keys can acquire the required information. The entire transaction process is open and transparent, and the blockchain has the characteristics of information imtampability and irreversibility, giving it the advantages of high confidentiality, strong security, and effective avoidance of false transaction behaviors. Moreover, the audit costs of the transactions were significantly reduced. Therefore, this study attempts to construct a two-party game evolution model of forestry carbon sink demand and supply based on blockchain technology. In the game process, participants always expect to introduce more favorable social norms into the game on the premise of interests [4]. Therefore, in this study, from the perspective of the participating traders and the demand side, whether emission reduction intention is actively introduced into the model design or the incentive and punishment mechanism is discussed from the supplier’s perspective. The model was designed based on whether the carbon sinks held and voluntarily put into the market for trading could meet market demand. Furthermore, the evolutionary mechanism of the game between the two sides, with the support of blockchain technology, is discussed.

This study aims to introduce blockchain technology into forestry carbon sink trading and further clarify the acceptance of blockchain technology by participating traders in the secondary market through the establishment of a game model. This will provide some references for the more efficient and perfect conduct of carbon sink trading and the development of the green economy. This study makes two major contributions to the literature. First, unlike previous studies, it focuses on the supply and demand of the secondary market, combines carbon sink trading with blockchain technology, establishes a game model of the supply and demand of forestry carbon sink trading from the perspective of traders, and discusses its evolutionary stability strategy. This method breaks through the application of carbon sink trading to the traditional trading model and simultaneously plays a complementary role in the application of blockchain technology in carbon sink trading. Second, through numerical simulations, MATLAB R2020b software is used to conduct a simulation analysis of transactions. Through changes in key values in the supply and demand game simulation diagram, their impact on the game evolution path can be intuitively observed to provide a theoretical reference for future research.

2. Literature review

In the outline of the 14th Five-Year Plan for 2021, blockchain is listed as one of the seven key industries of the digital economy in the chapter on “Accelerating Digital Development and Building Digital China.” The development of blockchain technology has received considerable attention from all walks of life and is regarded as the greatest invention for commercial and production relations in human history, mainly for the following reasons: First, it is a new trading model. Blockchain technology demonstrates a new direction for business models, business logic, and production organization relationships; breaks through the inherent trading mode of human society; builds a new trading platform, technological realization path, and tools [5]and provides more possibilities for trading modes and regulation. Second, it can effectively accelerate industrial innovation and development. The emergence and development of blockchain technology can strengthen the realization of peer-to-peer transactions in related fields, such as agriculture, logistics, and the energy industry, to improve transaction efficiency and overcome traditional trading barriers with technological advantages. For example, if applied to the energy industry, distributed production and energy trading can be realized, a multiparty trusted cooperation scenario can be built, the characteristics of the industry and pain points brought about by the transaction process can be grasped, the inherent shortcomings can be compensated, and opportunities to promote the construction of a more optimized transaction mode and accelerate industrial innovation and development can be provided. Therefore, seizing the opportunity for technology and industry integration and encouraging the government to legitimize enterprises’ green and low-carbon innovation through green research and development [6]play a significant role in innovation and development [7,8].

Currently, negative phenomena, such as a long issuance cycle, difficulty in realizing ecological value, low financing degree, and a single mode of forestry carbon sink market, are common in Chinese forestry carbon sink projects, and problems, such as “difficult transaction” of forestry carbon sink projects, have not been well addressed [9]. These problems indicate that the reform of the carbon sink trading mode is insignificant, and the transaction price is affected by carbon taxes, subsidies, and so on, so it has a more dynamic trend. On this basis, some researchers believe that dynamic carbon trading and pricing policies also play a positive role in accelerating carbon emissions reduction [10], but carbon taxes have increased the marginal effect of promoting the diffusion of low-carbon technologies [11]. For example, with the continuous development of distributed energy, problems such as “difficult trading” and “long cycle” will gradually improve. With the continuous optimization and improvement of the aforementioned problems, distributed transactions with small single-transaction volumes and high transaction frequencies will gradually become a new development trend. If such a transaction scale is incorporated into the previous transaction mode, it will greatly test the processing capacity of the central system because of its characteristics, such as increasing the difficulty of the decision of the transaction center and increasing the operation and maintenance costs of the equipment [12]. Distributed transactions with a blockchain can eliminate the need for a central system, and distributed transactions can realize distributed storage based on the following cryptography principle: Each block in the blockchain stores complete transaction data, and the generated data block can be used to verify the authenticity of the information and generate the next block. However, only the buyer has a system key that guarantees transaction security. Moreover, point-to-point transactions can be realized, and the entire process cannot be tampered with. The transaction process is simplified, thereby reducing transaction costs to a certain extent [13,14]. The advantages of blockchain are not only reflected in the above cases but also in the maximization of individual benefits. In a traditional centralized trading network, the data of the individuals and institutions involved in the transaction are nominally their own, but the interests and powers of the individuals and institutions are all owned by the centralized organization at an extremely low price or are even free to become the assets of the centralized organization, which is why the mobile Internet era has created many large companies. Data providers can only passively enjoy paid or free services and cannot share the benefits of development [5]. However, in blockchain transactions, the subjects of the transactions can participate as the biggest beneficiaries of the benefits, avoiding the phenomenon of a centralized organization acquiring assets or rights for free.

If blockchain technology is to be applied in more fields or scenarios, its extension must be continuously expanded, for example, by integrating smart contracts into functional combinations [15]. Moreover, to ensure the safety and reliability of the blockchain technology application environment in carbon sink trading, many security levels must be established to ensure the legitimate interests of the transaction subjects. First, ecological legislation should be constantly improved, regulatory mechanisms should be established, and supervision and constraints should be strengthened. Appropriate laws and regulations can guarantee the trading process, ensure the relevant rights and interests of both buyers and sellers, and promote the benign operation of the trading market. Second, capital channels should be expanded, and more trading objects and participants should be included to diversify the trading market. Third, a green credit system should be developed. The construction of a credit system provides risk analysis and other warning functions for both buyers and sellers in the trading process and is also a sign of the maturity of the trading market. Fourth, blockchain should be continuously expanding in the direction of ecological development; consequently, more research is needed to examine the current situation from the perspective of development [16].

3. Trading platform operation process

Taking Guangdong Carbon Exchange as an example, the transaction process of the traditional platform is shown in Fig. 1. After the buyer and seller sign the transaction contract, they submit it to a third party, the Guangdong Carbon Exchange, for filing, and subsequently undergo relevant procedures and pay the commission to the third party according to a certain percentage (depending on the actual situation). Some regions pay annual membership fees.

Unlike traditional trading platforms, carbon sink trading platforms with blockchain technology do not require the intervention of a third party, however, they use blockchain thinking to combine point-to-point transmission, asymmetric encryption, distributed ledgers, and other technologies. Every data storage node (i.e., from the time the transaction is initiated to the time it is completed) copies the data to the entire ledger (i.e., to each terminal) to ensure that the information is immutable and that the transactions are traceable throughout, thus breaking inherent trust-building difficulties. Trading platform architecture with blockchain technology as the underlying technology support can be divided into five levels: application, consensus, contract, data, and incentives. The corresponding transaction process is illustrated in Fig. 2. The seller authenticates his/her identity, obtains an identification tag on the blockchain trading platform, and certifies the number of carbon sinks that he/she can sell. If the buyer has a purchase need, a service demand block can be created after identity authentication and binding transaction accounts on the blockchain platform. Once the service demand block is created, the carbon sink trading hub automatically synchronizes the required trading volume and other information and starts intelligent matching according to the label information. Subsequently, a transaction between the buyer and seller is generated, and the seller sells to the buyer. After the buyer accepts the transaction, a transaction completion block is created in the blockchain according to the identity tag, and the transaction information can be traced. Finally, the seller and blockchain share the income, and the seller receives a reward according to the policy.

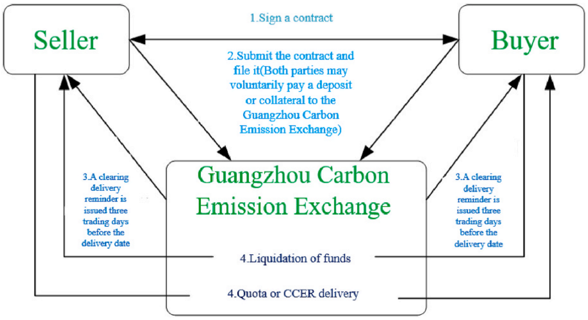


Fig. 1. Trading flowchart of the Guangzhou Carbon Emissions Exchange (Guangzhou Carbon Emissions Exchange).

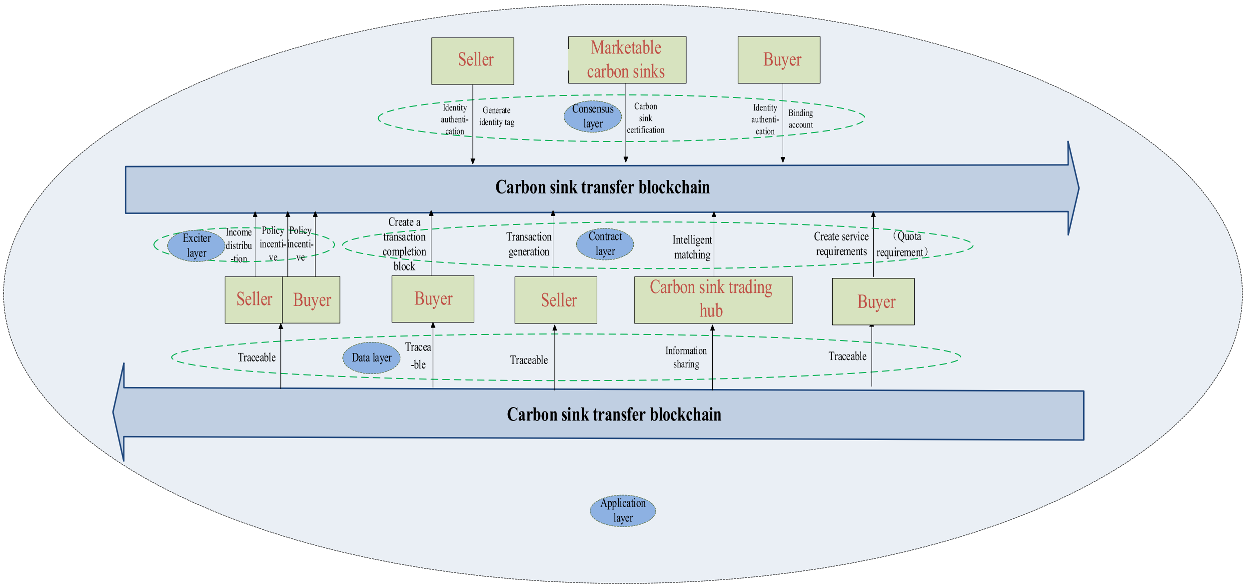


Fig. 2. Operation flow chart of the blockchain platform for forestry carbon sink trading.

4. Hypothesis and model construction

4.1. Problem description

In the main relationship of the forestry carbon sink trading market, supply, demand, balance, and imbalance are inevitable. The main situation is described as follows: when the carbon sinks available for sale in the market are sufficient or just enough to meet the demand of the party participating in the transaction, the supply can meet the demand; in contrast, when the amount of carbon sinks available for sale in the market is less than the amount of carbon sinks sought by the trading demander, the supply cannot meet the demand. In response to the advocacy of a green and low-carbon economy, some subjects that need to conduct carbon sink trading still face issues such as stealing emissions, multiple emissions, and non-emissions, according to policy requirements. In such cases, the government strictly supervises and sets penalties. When the demand side of the transaction actively responds to the policy and participates in the emission-reduction transaction according to relevant regulations and requirements, it is classified as active emission reduction. The government adopts an incentive mechanism and sets a reward coefficient. If the demand side actively participates in emission reduction but the carbon sink available for sale on the market fails to meet the demand side's purchase and there is still an excess proportion, a penalty is charged according to a certain percentage. However, this can still be regarded as active emission reduction. Accordingly, if the carbon sinks available for sale in the market can meet all or a certain proportion of the demand but the demand side still refuses or evades participation in the transaction for various reasons, it will be classified as a negative emission reduction and will be heavily fined. Additionally, the government can give a certain amount of bonus support to the trading subjects who voluntarily participate in the introduction of blockchain technology in the trading market.

4.2. Model assumption and parameter setting

4.2.1. Model assumption

Hypothesis 1: The main body of the model is the supply and demand for forestry carbon sink trading. Without the introduction of blockchain technology, carbon exchange can be regarded as the object of participation in a game model involving both parties. When blockchain technology is introduced, both suppliers join the blockchain by default as the transaction subject for transactions without considering other special circumstances, for example, only one party has introduced blockchain technology or selling on behalf of the other party. Due to the difference in the rationality degree between the two sides and the bounded rationality, the probability that the demand side actively reduces emissions is m, while the probability that the supply side fails to meet the demand side is n, resulting in m, n $\in$ [0,1]. Moreover, m_0 and n_0 represent the initial emission-reduction intention on the demand side and the initial available carbon sink on the supply side, respectively.

Hypothesis 2: When the amount of carbon sinks available for sale in the market can meet the demand, the demand is not greater than the amount available for sale, that is, $q \leq q_2$. When the amount of carbon sinks available for sale in the market cannot meet the demand, the demand is greater than the amount available for sale, that is, $q_1 < q_2$. When $q = q_2$, the default in the model is q.

Hypothesis 3: The demand side actively reduces emissions when blockchain technology is introduced. Under the advantages of decentralization, the supply and demand sides do not need to pay the membership fee or other excess fees to the third party; however, when blockchain transactions occur, the system calculates and withdraws the fees according to the number of bytes of the exchange. In this study, the number of bytes of exchange is replaced by the proportion of fees deducted. θ is regarded as the product of the transaction price and the proportion of fees deducted. Moreover, the proportion of fees deducted should be lower than the proportion of commissions and dues paid in centralized transactions. Therefore, when the demand side actively seeks the supply side to conduct the transactions, the supply side can provide a sufficient trading volume limit, and other factors are temporarily ignored, the demand side needs to pay $(\mathrm{pq}+\theta)$.

Hypothesis 4: When the block chain is implemented, if the demand side actively reduces emissions, the government will give a one-time subsidy (W) for infrastructure construction to both parties participating in the transaction and give a certain discount to the unit price of carbon sinks participating in the transaction according to the actual proportion of each participating party, with the preferential intensity being η. When the carbon sink of the supply side can meet the demand, both the supply and demand sides can receive the actual preferential income η pq. When the carbon sink of the supplier cannot meet the demand, the actual preferential income can be obtained by the supply and demand as $\eta\, pq_1$ and $q_1 \eta\, p\, \frac{q_1}{q}$, respectively. If the demand side does not reduce emissions, the government will provide the same amount of one-time infrastructure subsidies to the supply side but half the amount of subsidies to the demand side.

Hypothesis 5: When blockchain is implemented, if the demand side actively reduces emissions but the carbon sinks available for sale in the market cannot meet the demand, the excess proportion shall be charged with penalties with a punishment intensity of γ_1, and the actual penalty amount is $(q-q_1)\gamma_1 p$. If the demand side reduces emissions passively and refuses to participate in the transaction, the full amount of carbon sink required will be charged; that is, the actual penalty amount will be $pq\,\gamma_1$.

Hypothesis 6. Only those on the demand side who had demands were considered the research object. The carbon sink was ignored as the subject of the dividend expectations of investment products, and other disturbances were eliminated.

4.2.2. *Parameter setting*

The relevant parameters based on the above assumptions are listed in Table 1.

4.2.3. *Model construction*

Based on the above assumptions, when both suppliers of the forestry carbon sink trading market join blockchain technology, the game matrices of both suppliers and suppliers are as shown in Table 2.

As shown in Table 2, with the support of blockchain technology, π_{m1} and π_{m2} represent the expected returns when the demand side actively and negatively reduces emissions, respectively, and π_{n1} and π_{n2} represent the expected returns when the supply side cannot and can meet the demands, respectively.

(1) The expected income when the demand side actively reduces emissions can be calculated as shown in Equation (1):

$$\pi_{m1} = (npq_1 - npq)(\gamma_1 - 1) + np\eta\left(\frac{q_1^2}{q} - q\right) - pq - \theta k + W + pq\eta \tag{1}$$

The expected benefits of negative emission reduction on the demand side can be calculated as shown in Equation (2):

$$\pi_{m2} = \frac{W}{2} - pq\gamma_1 \tag{2}$$

The demand-side replication dynamic equation as shown in Equation (3):

$$F(m) = m(1-m)\left[(npq_1 - npq)(\gamma_1 - 1) + np\eta\left(\frac{q_1^2}{q} - q\right) + pq(\gamma_1 - 1 + \eta) + \frac{W}{2} - \theta k\right] \tag{3}$$

(2) The expected returns when the supplier cannot meet demand can be given as shown in Equation (4):

$$\pi_{n1} = mq_1 p(1+\eta) - m\theta k + W - Cq_1 \tag{4}$$

The expected return when the supplier can meet the demand can be calculated as shown in Equation (5):

$$\pi_{n2} = mqp(1+\eta) - m\theta k + W - Cq \tag{5}$$

The supply-side replication dynamic equation can be calculated as shown in Equation (6):

Table 1
Parameter symbols and meanings.

Symbol	Meaning	Symbol	Interpretation
p	Forestry carbon sink trading unit price.	C	Cost of reducing emissions per unit of carbon sink.
q	Forestry carbon sequestration demand.	γ_1	Blockchain execution unit penalty factor.
q_1	When the amount available for sale on the market cannot meet the demand, the supplier can provide the upper limit of forestry carbon sinks for trading.	θ	The transaction cost of converting bytes for a single transaction when the blockchain is executed.
q_2	When the amount available for sale on the market can meet the demand, the supplier can provide the upper limit of forestry carbon sinks for trading.	k	Number of transactions during blockchain execution.
		W	Blockchain technology infrastructure construction government one-time subsidy.
		η	Blockchain execution unit preferential coefficient.

Table 2
Game payment matrix between the supply and demand of forestry carbon sink transaction under blockchain technology.

		Demand side	
		Actively reduce emissions(*m*)	Negative emission reduction(1-*m*)
Supplier side	Unmet demand (*n*)	$q_1(p - C + \eta \mathrm{p}) - \theta k + W$ $-[pq_1 + \theta k + (q - q_1)\gamma_1 \mathrm{p}] + W + q_1 \eta p \frac{q_1}{q}$	$W - Cq_1$ $\frac{W}{2} - \mathrm{p}q\gamma_1$
	Meet demand (1-*n*)	$q(p - C + \eta \mathrm{p}) - \theta k + W$ $-(\mathrm{pq} + \theta k) + W + \eta pq$	$W - Cq$ $\frac{W}{2} - \mathrm{p}q\gamma_1$

$$F(n) = n(1-n)[mp(q_1 - q)(1+\eta) + C(q - q_1)] \tag{6}$$

5. Analysis of evolutionary stability strategy

According to the replication dynamic system stability analysis method proposed by Friedman (1991) [17], the Jacobian matrix of the supply and demand sides of the forestry carbon sink transaction was obtained when blockchain technology was added, as shown in Equations (7) and (8).

$$J = \begin{bmatrix} \frac{\partial F(m)}{\partial m}, & \frac{\partial F(m)}{\partial n} \\ \frac{\partial F(n)}{\partial m} & \frac{\partial F(n)}{\partial n} \end{bmatrix} \tag{7}$$

$$J = \begin{bmatrix} \begin{array}{l} (1-2m)\left[(npq_1 - npq)(\gamma_1 - 1) + np\eta\left(\frac{{q_1}^2}{q} - q\right)\right. \\ \left. + pq(\gamma_1 - 1 + \eta) + \frac{W}{2} - \theta k\right], \end{array} & m(1-m)\left[(pq_1 - pq)(\gamma_1 - 1) + p\eta\left(\frac{q_1^2}{q} - q\right)\right] \\ n(1-n)[p(q_1 - q)(1+\eta)], & (1-2n)[mp(q_1 - q)(1+\eta) + C(q - q_1)] \end{bmatrix} \tag{8}$$

$$\det J = \frac{\partial F(m)}{\partial m}\frac{\partial F(n)}{\partial n} - \frac{\partial F(m)}{\partial n}\frac{\partial F(n)}{\partial m} \tag{9}$$

$$trJ = \frac{\partial F(m)}{\partial m} + \frac{\partial F(n)}{\partial n} \tag{10}$$

According to Equations (9) and (10), the determinant and trace of the Jacobian matrix can be obtained to analyze the strategic stability points and dynamic changes on the supply and demand sides of forestry carbon sinks. As shown in Table 2, the carbon sink trading model under blockchain technology is affected by many factors, and all the parameters in the model are reasonable without loss of generality. Therefore, this study makes the following supplementary assumptions according to the actual situation. Hypothesis $\gamma_1 - 1 > 0$, where γ_1 is a positive integer >1, indicates that punishment is strong and multiplied when the blockchain is executed. According to the actual situation, the unit preference coefficient is $\eta \in (0,1)$; therefore, $\gamma_1 - 1 \neq 1 + \eta$ can be divided into the following

Table 3
Analysis of the stability point of the game system of supply and demand under Proposition 1.

Evolutionary equilibrium point	det J/trJ		Stable point or not
(1 , 1)	$\left[\mathrm{p}(\mathrm{q}_1 - \mathrm{q})(\gamma_1 - 1) + \mathrm{p}\eta\left(\frac{\mathrm{q}_1^2}{\mathrm{q}} - \mathrm{q}\right) + \mathrm{pq}(\gamma_1 - 1 + \eta) + \frac{\mathrm{W}}{2} - \theta\mathrm{k}\right]$ $[\mathrm{p}(\mathrm{q}_1 - \mathrm{q})(1 + \eta) + \mathrm{C}(\mathrm{q} - \mathrm{q}_1)] > 0$ $-\left[\mathrm{p}(\mathrm{q}_1 - \mathrm{q})(\gamma_1 - 1) + \mathrm{p}\eta\left(\frac{\mathrm{q}_1^2}{\mathrm{q}} - \mathrm{q}\right) + \mathrm{pq}(\gamma_1 - 1 + \eta) + \frac{\mathrm{W}}{2} - \theta\mathrm{k}\right]$ $-[\mathrm{p}(\mathrm{q}_1 - \mathrm{q})(1 + \eta) + \mathrm{C}(\mathrm{q} - \mathrm{q}_1)] < 0$	+/+	Unstable point
(1 , 0)	$-\left[\mathrm{pq}(\gamma_1 - 1 + \eta) + \frac{\mathrm{W}}{2} - \theta\mathrm{k}\right]\left[\mathrm{p}(\mathrm{q}_1 - \mathrm{q})(1 + \eta) + \mathrm{C}(\mathrm{q} - \mathrm{q}_1)\right] > 0$ $\mathrm{pq}(1 - \gamma_1) - \frac{\mathrm{W}}{2} + \theta\mathrm{k} + [\mathrm{p}(1 + \eta) - \mathrm{C}](\mathrm{q}_1 - \mathrm{q}) < 0$	+/-	ESS
(0 , 1)	$-\left[\mathrm{pq}_1(\gamma_1 - 1) + \mathrm{p}\eta\frac{\mathrm{q}_1^2}{\mathrm{q}} + \frac{\mathrm{W}}{2} - \theta\mathrm{k}\right]\left[\mathrm{C}(\mathrm{q} - \mathrm{q}_1)\right] > 0$ $\left[\mathrm{pq}_1(\gamma_1 - 1) + \mathrm{p}\eta\frac{\mathrm{q}_1^2}{\mathrm{q}} + \frac{\mathrm{W}}{2} - \theta\mathrm{k}\right] - \mathrm{C}(\mathrm{q} - \mathrm{q}_1) < 0$	−/+	Unstable point
(0 , 0)	$\left[\mathrm{pq}(\gamma_1 - 1 + \eta) + \frac{\mathrm{W}}{2} - \theta\mathrm{k}\right][\mathrm{C}(\mathrm{q} - \mathrm{q}_1)] > 0$ $\left[\mathrm{pq}(\gamma_1 - 1 + \eta) + \frac{\mathrm{W}}{2} - \theta\mathrm{k}\right] + \mathrm{C}(\mathrm{q} - \mathrm{q}_1) < 0$	+/+	Unstable point

two propositions for assumption, and the stable point of the game system of both sides is obtained.

Proposition 1. When blockchain execution conforms to $\left|p(q_1-q)(\gamma_1-1)+p\eta\left(\frac{q_1^2}{q}-q\right)-\theta k\right|> pq(\gamma_1-1+\eta)+\frac{W}{2}$ and $\left|p\eta\left(\frac{q_1^2}{q}-q\right)-\theta k-C(q-q_1)\right|< pq(\gamma_1-1+\eta)+\frac{W}{2}$, the influence of the discussion of the relevant evolutionary equilibrium points on the stability of the carbon sink trading system is as shown in Table 3.

The details are as follows:

Case 1:. *When m=1 and n=1, the demand side actively reduces emissions, whereas the supply side cannot meet demand. According to the assumptions above, the determinant is* $\left[p(q_1-q)(\gamma_1-1)+p\eta\left(\frac{q_1^2}{q}-q\right)+pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k\right]\left[p(q_1-q)(1+\eta)+C(q-q_1)\right]>0$. *Trace is* $-\left[p(q_1-q)(\gamma_1-1)+p\eta\left(\frac{q_1^2}{q}-q\right)+pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k\right]-[p(q_1-q)(1+\eta)+C(q-q_1)]>0$. *If the stable-point condition is satisfied,* $[p(q_1-q)(1+\eta)+C(q-q_1)]>0$ *is true. According to the actual situation,* $p(1+\eta)>C$ *and* $q_1-q<0$ *do not satisfy the conditions; thus, they are unstable points.*

Case 2: *When m=1 and n=0, the demand side actively reduces emissions and the supply side can meet demand; the determinant is* $-[pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k][p(q_1-q)(1+\eta)+C(q-q_1)]>0$. *Trace is* $pq(1-\gamma_1)-\frac{W}{2}+\theta k+[p(1+\eta)-C](q_1-q)<0$. *This holds true if* $pq(\gamma_1-1)+\frac{W}{2}-\theta k>0$ *is satisfied. According to the above assumptions, when the* $pq(\gamma_1-1)+\frac{W}{2}>\theta k$ *meets the conditions and conforms to the actual situation, it is a stable point.*

Case 3: *When m=0 and n=1, the demand side reduces emissions negatively, and the supply side cannot meet demand. According to the above assumption, the determinant is* $-\left[pq_1(\gamma_1-1)+p\eta\frac{q_1^2}{q}+\frac{W}{2}-\theta k\right]\left[C(q-q_1)\right]<0$, *and the trace is* $\left[pq_1(\gamma_1-1)+p\eta\frac{q_1^2}{q}+\frac{W}{2}-\theta k\right]-C(q-q_1)>0$. *If the condition of the stable point is met, it is true when it is* $\left[pq_1(\gamma_1-1)+p\eta\frac{q_1^2}{q}+\frac{W}{2}-\theta k\right]<0$, *which is contrary to the actual situation above; therefore, it does not meet the condition. Consequently, this was an unstable point.*

Case 4:. *When m=0 and n=0, the demand side reduces emissions negatively, whereas the supply side meets demand. Based on the above assumptions, the determinant is* $[pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k][C(q-q_1)]>0$, *and the trace is* $[pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k]+C(q-q_1)>0$. *However, this is not the case; therefore, it does not exist.*

Proposition 2. When the blockchain execution conforms to $\left|p(q_1-q)(\gamma_1-1)+p\eta\left(\frac{q_1^2}{q}-q\right)-\theta k\right|< pq(\gamma_1-1+\eta)+\frac{W}{2}$ and $\left|p\eta\left(\frac{q_1^2}{q}-q\right)-\theta k-C(q-q_1)\right|> pq(\gamma_1-1+\eta)+\frac{W}{2}$, a discussion of the relevant evolutionary equilibrium points under such a proposition results in the changes shown in Table 4.

The details are as follows:

Case 1: *When m=1 and n=1, the demand side actively reduces emissions, whereas the supply side cannot meet demand. Based on the above assumptions, the determinant is* $\left[p(q_1-q)(\gamma_1-1)+p\eta\left(\frac{q_1^2}{q}-q\right)+pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k\right]\left[p(q_1-q)(1+\eta)+C(q-q_1)\right]<0$, *and the trace is* $-\left[p(q_1-q)(\gamma_1-1)+p\eta\left(\frac{q_1^2}{q}-q\right)+pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k\right]-[p(q_1-q)(1+\eta)+C(q-q_1)]>0$. *That is, it is the opposite of the stable-point condition; therefore, it is an unstable point.*

The other three conditions are consistent with Proposition 1. Therefore, only when m=1 and n=0, that is, when the demand side actively reduces emissions and the supply side can meet the demand, is the stable point condition satisfied. This implies that in the trading system under blockchain technology, when the carbon sinks available for sale on the market evolve to cover the demand, the trading behavior of the demand side of the carbon sink will also evolve towards active emission reduction, and the evolutionary equilibrium point is E(1,0).

Table 4

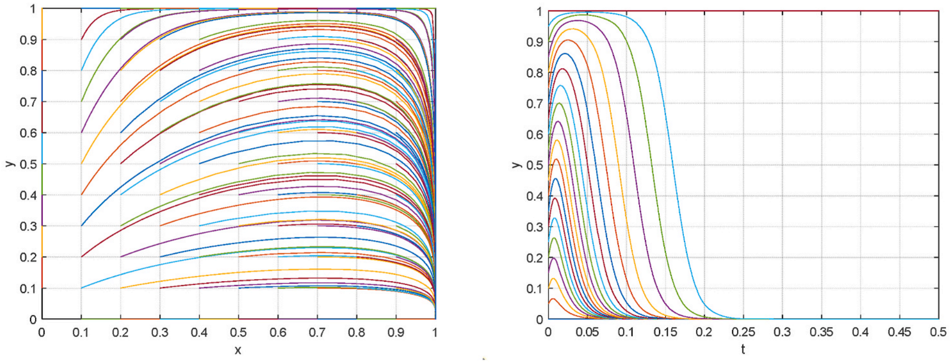
Analysis of the stable point of Proposition 2 game system between supply and demand

Evolutionary equilibrium point	det J/trJ		Stable point or not
(1 , 1)	$\left[p(q_1-q)(\gamma_1-1)+p\eta\left(\frac{q_1^2}{q}-q\right)+pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k\right]$ $[p(q_1-q)(1+\eta)+C(q-q_1)]>0$ $-\left[p(q_1-q)(\gamma_1-1)+p\eta\left(\frac{q_1^2}{q}-q\right)+pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k\right]$ $-[p(q_1-q)(1+\eta)+C(q-q_1)]<0$	−/+	Unstable point
(1 , 0)	$-\left[pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k\right]\left[p(q_1-q)(1+\eta)+C(q-q_1)\right]>0$ $pq(1-\gamma_1)-\frac{W}{2}+\theta k+[p(1+\eta)-C](q_1-q)<0$	+/-	ESS
(0 , 1)	$-\left[pq_1(\gamma_1-1)+p\eta\frac{q_1^2}{q}+\frac{W}{2}-\theta k\right]\left[C(q-q_1)\right]>0$ $\left[pq_1(\gamma_1-1)+p\eta\frac{q_1^2}{q}+\frac{W}{2}-\theta k\right]-C(q-q_1)<0$	−/+	Unstable point
(0 , 0)	$[pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k][C(q-q_1)]>0$ $[pq(\gamma_1-1+\eta)+\frac{W}{2}-\theta k]+C(q-q_1)<0$	+/+	Unstable point

6. Evolution simulation

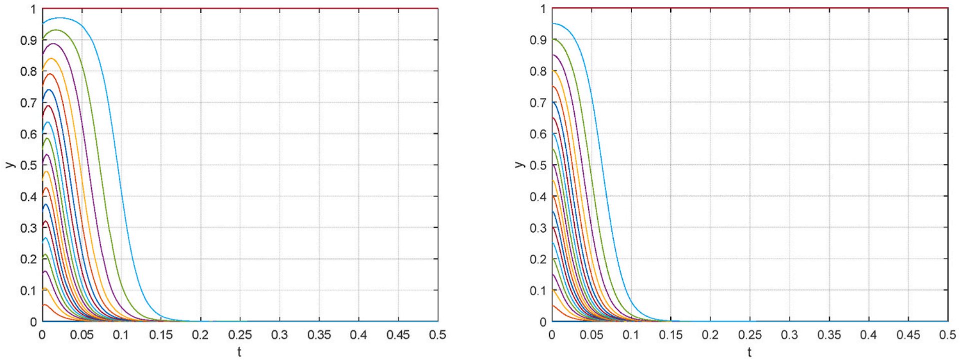
6.1. Parameter setting

As an offset mechanism, the CCER has the characteristic of widely expanding participants and promoting sound development in forestry and other environmentally friendly industries. Therefore, using data from Guangdong Province is persuasive for studying forestry carbon sink trading models. According to the relevant information disclosure of the Guangzhou Carbon Emission Trading Center and the transaction situation of CCER in the past year as the data reference, the following values are set for this model: According to the data on the CCER projects disclosed by the Guangzhou Carbon Exchange from July 2021 to July 2022, the number of projects issued increased from 358 to 391, with a total transaction volume of 9,363,315 million tons. Because the CCER project was the mainstream project when carbon-neutral subjects selected offsetting products, the total transaction volume of the CCER project in nearly a year was considered the demand for forestry carbon sinks in this study. Moreover, the average transaction price of the Guangdong carbon market disclosed on July 25, 2022, was taken as the unit price of forestry carbon sinks, which was $p = 79$ yuan/ton and $q = 9.36$ million tons. Additionally, "year" was considered the cycle, and each project was regarded as only one transaction a year, that is, $k = 391$ times. According to relevant information disclosure, the cost of carbon dioxide reduction through forestry carbon sequestration was approximately $10/ton, which was approximately $C = 67$ yuan/ton. According to the increase in the transaction price from 2022 to 2021, the inflation rate was approximately 28.14 %, which can be converted when the carbon sinks available for sale in the market cannot meet the demand, and after the round, $q_1 = 6.73$ million tons. Because of the large number of carbon sink transactions conducted by the blockchain, this study considered pq as the base and converted the number of bytes accounted for by exchanges into a withdrawal ratio of 0.2 %, which was relatively more intuitive. Other parameters were specified at the same time, that is, $\gamma_1 = 2$, $W = 1$ million yuan, and $\eta = 0.2$.



(a) Dynamic evolution path of the game between two sides

(b) Demand-side decision evolution process (x=0.3)



(c) Demand-side decision evolution process (x=0.5)

(d) Demand-side decision evolution process (x=0.5)

Fig. 3. Simulation diagram of forestry carbon sink trading supply and demand game under the blockchain technology.

6.2. Simulation analysis

MATLAB R2020b software was used to conduct the simulation and analyze the evolution of the game. The initial values of x and y were set to zero, and the cycle step size was set to 0.1. The operational results are presented in Fig. 3 (a). Additionally, to understand more intuitively and clearly whether the carbon sinks available for trading in the market can meet the trading demand, the strategy evolution process on the demand side over time differed. The cycle step size was set to 0.05, and the probabilities of meeting the demand were set to 0.3, 0.5, and 0.7. A trend evolution diagram of the demand-side for blockchain transactions after operation is shown in Fig. 3 (b), (c), and (d).

As shown in Fig. 3 (a), the regional paths converge to (1,0) to different degrees; that is, when the demand side actively reduced emissions, the carbon sinks available for sale in the market could meet demand. Moreover, Fig. 3 (b), (c), and (d) show that the carbon sinks available for sale in the market that can meet the demand are correlated with the selection attitude of the demander. When $x = 0.3$, the demanders hesitated to make decisions and participated in blockchain transactions to reduce emissions. With a continuous increase in the value of x, the probability that the carbon sinks sold in the market can meet the demand side gradually increased from 0.3 to 0.7, and the demand side's hesitation gradually decreased. Therefore, they participate in blockchain transactions more decisively. All the populations converged to (1,0). Furthermore, the participating traders generally have a positive attitude towards the access to blockchain technology and believe that the dynamic relationship between the two is as follows: the more carbon sinks available for sale in the market can meet demand, the more positive the demand side will have a trading attitude.

7. Conclusion

This study constructed a forestry carbon sink trading game model using blockchain technology from the perspective of traders and simulated the evolution path using MATLAB R2020b software. The key conclusions are as follows: (1) With the support of policy encouragement, in addition to other external influences (this study only considered traders' real demand for buying and selling rather than other interference, such as investment), traders held a positive attitude toward transactions supported by blockchain technology and eventually converged toward (1, 0). This demonstrates that the introduction of blockchain technology to forestry carbon sink trading is feasible. Moreover, the higher the willingness of the participating traders to conduct carbon sink trading, the more they can promote the development of the trading market in healthy and positive directions. (2) The number of carbon sinks available for trading in the market and the attitudes of the participating traders show dynamic changes. Thus, the greater the probability that the supply can meet the demand side, the more determined the demand side is to participate in the transaction. Specifically, when the carbon sink available for sale in the market meets the demand, the behavior probability of the demand side participating in the transaction will be infinitely close to 1. Therefore, a positive relationship exists between the extent to which the supply side can sell in the market and whether the demand side participates in transactions. Based on this, the application of blockchain technology in the forestry carbon sink trading market should be developed and improved in the following ways: First, forestry carbon sink trading needs local government support and an effective trading system to prosper. Using the pilot trading area as an example, we base policy incentives on single transaction volume and number of transactions and divide carbon sinks into pre-, in-, and post-transaction stages. The source of the incentive money can be provided by the government and by the relevant enterprises related to and benefiting from carbon sink trading, according to the policies formulated based on the structure and content of the transaction evaluation system. Therefore, the virtuous cycle of the forestry carbon sink trading market and its development should be promoted. Second, the characteristics of blockchain technology and carbon sink trading should be utilized to organically combine the two and propose a new and more suitable transaction measurement standard. Blockchain transactions are measured by the number of bytes accounted for by the exchange, while carbon sink transactions are measured by units, such as "tons." According to the actual situation of carbon sink trading volume, when measuring the number of bytes of transactions, blockchain can endorse enterprises with carbon sink assets and initiate a "green channel." Therefore, the transaction process is efficient, open, and transparent; transaction costs are also more favorable. Third, the focus should be on cultivating interdisciplinary talent and optimizing resource allocation in the blockchain field. A sound development in carbon sink trading cannot be separated from the mutual support of multiple disciplines. Therefore, the inclusion of polygonal professionals and the coordination and cooperation between society and other aspects have become indispensable links while employing blockchain technology in the carbon sink trading market. Moreover, introducing and applying blockchain technology will make the trading mode constantly ideal and improve, and it will certainly advance the forestry carbon sink trading market to a new level. Due to the limitations of the data that can be disclosed in the current trading cases, our future research direction should focus on applying more perfect theories to practice, checking the gaps in continuous design and improvement, so as to establish a forestry carbon sink trading model that is more in line with the needs of green economic development. Additionally, while developing the blockchain technology, we gradually realized that socioeconomic development does not entirely depend on the size of the country. More importantly, a strategic vision requires seizing development opportunities, formulating effective policies, creating a favorable trading environment, and fostering future growth for both industry and nation. With the continuous advancement of blockchain technology, its application in emerging fields and continuous attempts will surely promote the emergence, development, and growth of more industries. As a crucial area of development, carbon sink trading can protect the interests of participating traders, break traditional barriers by exploiting the "east wind" of blockchain technology, and improve traders' trust in blockchain technology. This will promote the sound development of China's green economy and have a far-reaching impact on this field.

Ethics declarations

All participants provided informed consent to participate in the study.

Data availability statements

The original data related to this manuscript comes from the CCER project data from July 2021 to July 2022 disclosed by Guangzhou Carbon Emission Rights Exchange. The raw data is stored in a publicly available repository. All data generated or analyzed during this study are included in this published article.

CRediT authorship contribution statement

Song yukun: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Wu Haiquan:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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