The Economic Feasibility of Blue Carbon Cooperation in the South China Sea Region

ABSTRACT:Coastal Blue Carbon is the carbon stored in mangroves, tidal marshes and seagrass meadows. There is an urgent need to protect the coastal ecosystem by developing Blue Carbon economy. In this paper, we investigate the feasibility and mechanism of the Blue Carbon cooperation in the South China Sea Region (SCSR[[1]](#footnote-1)) from an economic angle. We utilize the paradigm of Cobb-Douglas production to stimulate Blue Carbon development and mathematically prove the feasibility of such a cooperation strategy. The Shapley value in game theory is further applied, which not only confirms the reality of this cooperation but also provides an allocation mechanism of the cooperation benefits. The results suggest that there exists a profitable opportunity for the Blue Carbon cooperation in the SCSR. Further discussion and suggestions are provided in promotion of research focus on the Blue Carbon cooperation.

*Keywords:*Blue Carbon; South China Sea; cooperative game; Shapley value

**1. Introduction**

Coastal Blue Carbon is defined as the carbon stored in mangroves, tidal marshes and seagrass meadows [1]. There is an urgent need to protect the coastal ecosystem by developing Blue Carbon economy. In particular, climate change has been one of the most significant challenges humanity is facing. With the United States withdrawal in June 2017 from the Paris Agreement, a main international response to climate change, it has posed challenges for Contracting States to adopt a domestic environmental law with an independent contribution to energy conservation and emission reduction to solve global climate problems. Therefore, seeking to solve the path and method of global warming through international cooperation has become an urgent issue in the 21st century.

Two effective ways to curb climate change are increasing carbon absorption from the end and reducing carbon emissions from the source. While some countries contribute most of their efforts to reducing carbon emission, there are others developing alternative effective and sustainable way by involving Blue Carbon sequestration to increase carbon absorption. Blue Carbon[[2]](#footnote-2), i.e, the carbon stored in the coastal ecosystem, is the most effective and sustainable approach for carbon storage. It has been reported that the rates of transferring and storing carbon dioxide from the atmosphere and ocean by Blue Carbon can be almost four times higher than that in tropical forests [1].

Our planet is, however, losing its coastal ecosystems at rates of up to four times higher than terrestrial forests [1]. Since the turn of the 19th century, it is estimated that the conversion to other land has lost half of the mangroves and tidal marshes and 29% of seagrass meadows [1], and at current conversion rates, more than 30% of the remaining tidal marshes and seagrasses and almost all of the mangroves will disappear in the next century [2]. Therefore, there is an urgent need for preventing further destruction and degradation, which requires international cooperative protection and development of coastal ecosystems.

The development of Blue Carbon needs global effort. In particular, note that Blue Carbon sequestration is a technology that uses carbon sequestration mechanisms of marine organisms and microbes to produce carbon sinks. When there is an international trading market established and a suitable measurement and pricing mechanism for carbon sink product, the Blue Carbon development would become an efficient production activity with economic value, in line with the law of economic system operation. Besides, the marine resources have traditionally been treated as common property. For example, the fishery (which can be used to develop Blue Carbon) in high seas, counting for 60% of the ocean, is hard to be developed without international cooperation since high seas are outside national jurisdiction. Therefore, it can be seen from the perspective of the economic feasibility and cooperation necessity that, the international Blue Carbon cooperation is an effective solution for climate change.

The SCSR is the most important area in the world for Blue Carbon development. This is because it has a high Blue Carbon coverage rate and has suffered from a serious loss in recent years [1, 3]. In addition, the SCSR is an area of the South China Sea Silk Route, one of the two main routes of the Maritime Silk Road, being a significant bridge for international trade and cultural communication between the East and the West. The development of Maritime Silk Road and the establishment of the ASEAN[[3]](#footnote-3)–China Free Trade Area indicate that these countries around the SCSR have close connections in cross-countries trade and culture. While there are also some territorial disputes in the SCSR between China and the ASEAN countries like Brunei, Malaysia, Indonesia, the Philippines, and Vietnam [4], the establishment of Blue Carbon Cooperation Mechanism in the SCSR can promote their negotiations and relieve the tension.

The remaining of this paper is organized as follows. The next section is a literature review on Blue Carbon. In the third section, we apply a paradigm of the Cobb-Douglas production model and a cooperative game model in game theory to test the feasibility of Blue Carbon cooperation. The use of the Shapley value to obtain the value allocation for the cooperation is provided in the fourth section. Then in the fifth section, empirical data analysis for the three countries around the SCSR is made to illustrate the potential for Blue Carbon cooperation. The sixth section summarizes potential cooperation and explores possible mechanisms to promote Blue Carbon cooperation between countries in the SCSR.

**2. Literature review**

“Blue Carbon” has already received extensive attention from scholars. The report joint released by UNEP, FAO, UNESCO and IOC[[4]](#footnote-4): “Blue Carbon: The Role of Healthy Ocean in Binding Carbon—A Rapid Response Assessment” summarized the research and practice in Blue Carbon from six aspects including Carbon fixation, ocean and climate, blue carbon, status quo, meaning to human society and changing path [5]. The report regards blue carbon as a product with public economic attributes, which indicates global efforts are needed in Blue Carbon development. Therefore, the present article uses the fact that Blue Carbon is a public product to argue the possibility of its international cooperation.

Researches have been made in Blue Carbon development mechanisms. Atwood *et al.* [6] suggested that marine predators have a significant influence on vegetated coastal ecosystems, indicating that coastal Blue Carbon can be protected by developing herbivores like fish and crab; the corresponding aquaculture can also compensate the opportunity cost of losing alternative ecosystem development. Moreover, fishery itself can increase carbon sink, it is another Blue Carbon. As an effective way of producing value and promoting carbon sequestration, the fishery has been highly concerned. Tang *et al.* [7] studied the effect of “Carbon Sink Fishery”, which can promote aquatic organisms to absorb carbon from water, then remove the carbon that has been converted into biological products by harvesting. Cullis-Suzuki *et al.* [8] studied fishery management in high seas, implies the need for international regulation for fishing in high seas. And international fishery cooperation in high seas has already been examined to be feasibleby Kaitala *et al* [9]. Carbon sink fisheries have the characteristics of the primary industry, and its production not only depends on inputs like capital and fishing area but also depends on certain technologies such as breeding technology, therefore the present article uses Cobb-Douglas production function, a production function considered total factor productivity, to model Blue Carbon development.

Capturing the monetary value of carbon credits on the international carbon market could provide a basis for Blue Carbon international trading and cooperation. Ullman *et al.* [10] studied the Blue Carbon market mechanism by applying a climate change policy—regulated cap-and-trade schemes, which regulate the maximum permitted green gas emissions each entity can have; this limit, or cap, is allocated or sold to entities in the form of credits which represent the right to emit a specific volume of the gas. The existence of carbon credits, which can be represented as currency in the economic model, indicates there is a need for Blue Carbon economy research, so this article analyzes the Blue Carbon sequestration from a perspective of economics.

Researchers have already found Blue Carbon production can be remunerative. Murray *et al.* [11] built a model to estimate the net payoff of Blue Carbon development by comparing the Blue Carbon value versus the cost of protection, and provided country-specific estimates of net economic return (present value of benefits minus present value of cost) for mangrove mitigation, from which it can be conjectured that the net payoff of Blue Carbon can be positive if the carbon price is above a certain level. While it only considered the model for individual countries, the present article changes the model by using an economic production model - using the Cobb-Douglas production function to represent the process of producing value through Blue Carbon protection, and ignores the opportunity cost and other costs (assuming they have been compensated by the ecological compensation mechanism such as developing fishery), and further researches the feasibility of cooperative Blue Carbon development.

In the research of applying Shapley value to the cooperative game, Dusit *et al.* [12] studied the resource management problem based on the bankruptcy game, which is a special type of an N-person cooperative game. It analyzed the stability of the allocation by using the concept of the core and the distribution by using the Shapley value. Our article applies the same logic to Blue Carbon cooperation, studies the feasibility of cooperation by both mathematical proof and the use of empirical data, and provides the Shapley distribution among countries in Blue Carbon cooperative game.

Scholars have also studied the policy and method for Blue Carbon management. In the report of PEMSEA[[5]](#footnote-5), there are some recommendations for countries to incorporate Blue Carbon ecosystems into integrated coastal management climate response, biodiversity conservation, and Blue Carbon economy plans [1]. From this, it can be observed that there is a possibility to enact cooperative action between countries or international organizations such as PEMSEA and the Sustainable Development Strategy for the Sea of East Asia (SDS-SEA). It also suggested that there are three main ways to advance the management of Blue Carbon ecosystems by awareness building, knowledge exchange and acceleration of practical action. Based on this, our article further assumes that in cooperation, the technology can be shared unconditionally so that low technology level countries would be more willing to take part in the cooperation.

The literature review finds that scholars are mainly concentrating on the management and policies of Blue Carbon for individual countries. Based on existing research, this article analyzes Blue Carbon from an economic angle, considers the possibility of cooperation between different countries, builds a model of Blue Carbon cooperative game, further analyzes its allocation and provides possible policies that can promote cooperation. It provides a theoretical basis for the Blue Carbon international policy of cooperation in the management of Blue Carbon ecosystems.

**3. An economic model and the** **feasibility of Blue Carbon cooperation**

*3.1 An economic paradigm for Blue Carbon production*

The production of blue carbon relies on the biochemical activities of marine organisms and microorganisms to convert carbon dioxide in the air into organic carbon and store it in the ocean. On the one hand, the production of blue carbon sinks is distributed with the area of Blue Carbon resources like seaweed, beach wetlands, and mangroves. On the other hand, coastal ecosystems are affected by terrestrial carbon sinks. Inadequate maintenance of seaweed, tidal flats, mangroves, and marine aquaculture also leads to a decline in carbon sinks, and these governance and aquaculture efficiencies require capital investment and technology development. Therefore, we can assume the economic factors of Blue Carbon production are mainly Blue Carbon area, capital, and technology level of protecting and utilizing Blue Carbon, and the income function of the blue carbon-producing country is replaced by the Cobb-Douglas production function.

We consider the Blue Carbon area as an input in Blue Carbon model, it is because if not use it in Blue Carbon activity, countries would use these Blue Carbon resource to generate other profits, for example, in some countries, people may use mangrove to produce timber rather than protecting mangrove for Blue Carbon. There is an opportunity cost for protecting Blue Carbon area, so the original Blue Carbon area is also an input in Blue Carbon production activity.

The paradigm ofCobb–Douglas production function was developed and tested against statistical evidence by Charles Cobb and Paul Douglas during 1927–1947 [13]. In its most standard form of production for a single good with two factors, the function is Y=ALαKβ, where Y = total production, L = labor input, K = capital input, A = total factor productivity and usual depreciation by utility in day after, α and β are the output elasticities of capital and labor, respectively. When α+β=1, the function shows constant returns to scale.

In the present article, we propose that the payoff for protecting and utilizing the Blue Carbon ecosystem can be represented by the paradigm of Cobb–Douglas production function with constant returns to scale. That is,

 v*i*=A*iXi*αY*i*1-α,

where v*i* is the payoff for country *i*, A*i* is the technology level of utilizing coastal ecosystem to store Blue Carbon in different countries, *Xi* is the effective Blue Carbon area in the country *i*, and Y*i* is the capita that country *i* can offer in Blue Carbon protection. In reality, the payoff can be represented by Blue Carbon offset credits [6]. Note in this model that *Xi*>0, Y*i*>0, α∈(0,1), *i*={1,2,3…n}.

*3.2 The basic concept of cooperative game*

Denote by the ordered pair (I,v) a cooperative game, where I={1,2,…,n} is a set of all participants, with a coalition S being a subset of I, S$⊂$I, taking I as the grand coalition, and *v* is a characteristic function which is a mapping from 2I=$\{s|s⊂I\}$ to the real set *R*. The value distribution function $∅\_{i}$*(v)* is defined as the value of participant *i* with the characteristic function *v*, and denote $∅$=[$∅$1*(v)*,…,$∅$*i(v)*,…,$∅$*n(v)*].

*3.3 The assumption of Blue Carbon cooperative game in SCSR*

The distribution of blue carbon resources is relatively concentrated and extensive in the South China Sea, as the South China Sea and the land-based countries of Southeast Asia have rivers connected, the eutrophication of river water injected into the land of the country will affect the carbon sequestration capacity of mangroves, salt algae, and wetlands, and also ASEAN often takes the status of a whole country as a participant in international affairs, so it is possible to participate in the cooperation between the 10 ASEAN countries and China. That is, the maximum of i is set as 11, which means 11 countries including China, Vietnam, Thailand, Cambodia, Singapore, Brunei, Philippines, Indonesia, Malaysia, Laos, and Myanmar.

*3.4 The feasibility of Blue Carbon cooperation: Theoretical justification*

In the Blue Carbon cooperative game, it is assumed that, in the cooperation, all the participants in a certain area are willing to take part (grand coalition) since climate change is a common problem for all human beings with sharing of technology in cooperation. In this article, cooperation is considered feasible if the total value obtained from cooperation is greater than or equal to the total value of non-cooperation.

The feasibility of the cooperative game in the Blue Carbon production model is examined as follows:

Two scenarios:
(1) A non-cooperative game, in which all the countries separately protect and make use of the Blue Carbon. Here the social payoff of the Blue Carbon is just the sum of the payoffs in different countries:

v(N)=$\sum\_{i}^{n}v\_{i}$=$\sum\_{i}^{n}($Ai$X\_{i}$α$Y\_{i}$1-α), *X*i>0, $Y\_{i}$>0, i∈{1,2,3,…n}, α∈(0,1)

(2) A cooperative game-grand coalition, in which all the countries join the cooperation. Only the grand coalition is considered, which has the highest payoff because of the super-additivity of Blue Carbon cooperation model (see Subsection 4.2). All the countries share their technology for utilizing coastal ecosystem to store Blue Carbon, so the technology level in the cooperative game model is Amax, the highest technology level among countries. The effective Blue Carbon area, the capital, and the money in the cooperative model are just the sum of different countries’ values.

v(I)=Amax$ (\sum\_{i}^{n}X\_{i})$α ($\sum\_{i}^{n}Y\_{i})$1-α, $X\_{i}$>0, $Y\_{i}$>0, i∈{1,2,3,…n}, α∈(0,1)

This article considers the condition for the feasibility of the Blue Carbon cooperation as the payoff in the cooperative game should be greater than or equal to the one in the non-cooperative game, that is

v(I)=Amax$ (\sum\_{i}^{n}X\_{i})$α ($\sum\_{i}^{n}Y\_{i})$1-α≥v(N)=$\sum\_{i}^{n}v\_{i}$=$\sum\_{i}^{n}($Ai$X\_{i}$α$Y\_{i}$1-α),

which can be proved as follows.

Firstly prove

Amax($X\_{1}$+$X\_{2}$)α($Y\_{1}$+$Y\_{2}$)1-α≥A1$X\_{1}$α$Y\_{1}$1-α+A2$X\_{2}$α$Y\_{2}$1-α.

Since

Amax≥A1, Amax≥A2,

the inequality above can be simplified by proving

Amax($X\_{1}$+$X\_{2}$)α($Y\_{1}$+$Y\_{2}$)1-α≥Amax$X\_{1}$α$Y\_{1}$1-α+Amax$X\_{2}$α$Y\_{2}$1-α,

which is

($X\_{1}$+$X\_{2}$)α($Y\_{1}$+$Y\_{2}$)1-α≥$X\_{1}$α$Y\_{1}$1-α+$X\_{2}$α$Y\_{2}$1-α.

Divide both sides by the value of the left-hand side,

Then we can get:

1≥$\frac{X\_{1}^{α}}{(X\_{1}+X\_{2})^{α}}\frac{Y\_{1}^{1-α}}{(Y\_{1}+Y\_{2})^{1-α}}+\frac{X\_{2}^{α}}{(X\_{1}+X\_{2})^{α}}\frac{Y\_{2}^{1-α}}{(Y\_{1}+Y\_{2})^{1-α}}$

Denoting u1=$\frac{X\_{1}}{X\_{1}+X\_{2}}$, v1=$\frac{Y\_{1}}{Y\_{1}+Y\_{2}}$, u2=$\frac{X\_{2}}{X\_{1}+X\_{2}}$, v2=$\frac{Y\_{2}}{Y\_{1}+Y\_{2}}$,

we can see that

u1+u2=1, v1+v2=1 .

Therefore, we need to show

1≥u1αv11-α+u2αv21-α,

1=u1$·α$+v1$·\left(1-α\right)+$u2$·α$+v2$·\left(1-α\right)$≥u1αv11-α+u2αv21-α.

Now we only need to prove

u1$·α$+v1$·\left(1-α\right)$≥u1αv11-α, u2$·α$+v2$·\left(1-α\right)$≥u2αv21-α

Proving the above is equivalent to showing

*x*$·α$+y$·\left(1-α\right)$≥*x*αy1-α.

Considering the log of the right-hand side of the above,

log(*x*αy1-α)=αlog*x*+(1-α) logy<log[α*x*+(1-α)y],

which is true since the log is a concave function.

 The log function monotone property implies [14]

*x*$·α$+y$·\left(1-α\right)$>*x*αy1-α.

So now we can get

($X\_{1}$+$X\_{2}$)α(Y1+Y2)1-α≥$X\_{1}$α$Y\_{1}$1-α+$X\_{2}$α$Y\_{2}$1-α.

Then

$X\_{1}$+$X\_{2}$+$X\_{3}$)α($Y\_{1}$+$Y\_{2}$+$Y\_{3}$)1-α≥($X\_{1}$+$X\_{2}$)α($Y\_{1}$+$Y\_{2}$)1-α+$X\_{3}$α$Y\_{3}$1-α≥$X\_{1}$α$Y\_{1}$1-α+$X\_{2}$α$Y\_{2}$1-α+$X\_{3}$α$Y\_{3}$1-α.

Then similarly, we can get

$(\sum\_{i}^{n}X\_{i})$α($\sum\_{i}^{n}Y\_{i})$1-α≥$\sum\_{i}^{n}(X\_{i}$α$Y\_{i}$1-α) .

So

Amax$ (\sum\_{i}^{n}X\_{i})$α($\sum\_{i}^{n}Y\_{i})$1-α≥$\sum\_{i}^{n}($Ai$X\_{i}$α$Y\_{i}$1-α) .

Therefore, the feasibility exists in this Blue Carbon cooperation model. This indicates that the cooperation in Blue Carbon production can generate a higher benefit than what it can generate without cooperation.

It should be noted that the proof excludes the effect of the improvement of “A” in cooperation, which is the technology level of utilizing coastal ecosystem to store Blue Carbon. If this factor is considered, the difference between cooperation and non-cooperation would be larger and the Blue Carbon cooperation would be more profitable. In reality, the technology gap between different counties can be very significant, and so a small addition in input can generate a much higher benefit than before because of the significant improvement of the technology level. Therefore, if the leading country is willing to share their information in cooperation, and other countries contribute to their effect on natural resource and capital, there would be a satisfactory cooperative outcome.

Based on this conclusion, we will further study the allocation of the benefits generated by Blue Carbon cooperation in order to make the cooperation more effective.

**4. The allocation of Blue Carbon cooperation**

*4.1 Definition*

The Shapley value set, denoted by $∅$=[$∅$1,…,$∅$*i*,…,$∅$*n*] for *n* countries, in which $∅$*i* is the cooperation distribution to country *i*, is a concept of the solution in cooperative game theory, which was introduced by Lloyd Shapley in 1953 [15]. It considers the concept of fairness in value functions:

(1) $\sum\_{i\in A}^{}∅\_{i}(v)$=*ν*(A)

(2) if there exist i and j such that *ν*(S∪{i})=*ν*(S∪{j}) and i, j$\notin $S, then $∅$*i*(*ν*) = $∅$*j*(*ν*)

(3) if there exists an i such that *ν*(S)=*ν*(S∪{i}) for S without i, then $∅$*i*(*ν*)=0

(4) if *u* and *ν* are characteristic functions, then $∅$(*u*+*ν*) =$∅$(*u*)+$∅$(*ν*).

Based on these properties, the Shapley value $∅$=[$∅$1,…,$∅$*i*,…,$∅$*n*] can be computed as follows [15].

$$∅\_{i}\left(v\right)=\sum\_{S⊂I}^{}\frac{\left(\left|S\right|-1\right)!\left(n-\left|S\right|\right)!}{n!}\left[v\left(S\right)-v\left(S\i\right)\right], i=1,2,…n$$

where A is any set of participants, *n* is the total number of participants, $\left|S\right|$ is denoted as the number of participants in the coalition S, S$\i$ is the coalition of all participants in S excluding *i*.

By knowing how to use it, our next step is to test whether the Shapley value is suitable for the Blue Carbon cooperation allocation.

*4.2 The practicability of the Shapley value in Blue Carbon cooperative model*

In the literature, there are several methods that can be used to solve the N-person cooperative game. In this article, we choose the Shapley value since from simulations we can observe that the Shapley value provides a relatively fair solution, compared with other methods [11]. In fact, Shapley [15] already showed that *the Shapley value* is the unique payoff vector that is efficient, symmetric, additive, and assigns zero payoffs to dummy players. Meanwhile, since we consider Blue Carbon as a production activity, participants contribute inputs like capital and money in the cooperation, then Shapley value provides a fair mechanism for payoff allocation, in which their payoffs depend on their contributions.

We are showing that the Shapley value is also individually rational for the Blue Carbon cooperation [[6]](#footnote-6). Note that the Shapley value for a super-additive[[7]](#footnote-7) game is individually rational [16], while from the proof in Section 3.2 we can actually conclude that the Blue Carbon production function is just super-additive[[8]](#footnote-8).

The super-additivity property of the Blue Carbon production model also indicates that the grand coalition has the highest payoff, so, generally, all the countries should join the Blue Carbon cooperation to protect our planet.

A disadvantage of the Shapley value method is that it needs too much information when *n* is large. Fortunately, in the Blue Carbon cooperation case, *n* is often limited since the participant is usually a country or an international organization, the number of which would not be too large.

Based on the analysis above, the Shapley value is a suitable method for allocation of the benefits generated from the Blue Carbon cooperation. Our analysis suggests all the countries in the SCSR should join the cooperation and negotiate the profit allocation using the concept of the Shapley value.

**5. An illustration of the feasibility and distribution of the Blue Carbon cooperation among China, Indonesia, and Thailand**

*5.1 Choice of example Countries*

To illustrate our algorithm, we demonstrate possible Blue Carbon cooperation among China, Indonesia, and Thailand. We choose these three countries because, among all the countries in the SCSR, they have significant roles in developing Blue Carbon cooperation. The coverages of mangrove in these three countries are in the top ten in East Asia, with Indonesia’s of the highest. China has the leading technology for Blue Carbon among SCSR countries, while Thailand is in a geographical position of linking China and Indonesia.

Meanwhile, the estimated soil carbon emissions from their concerted former coastal tidal wetlands are also in the top ten in East Asia. In 2011, China had 462 MMt soil carbon lost, which is the highest among the East Asia countries, while Indonesia and Thailand had 116.3 and 20.6 MMt soil carbon lost, respectively[1]. In 2016, these three countries and others including Singapore had already held a “Think Tank Seminar on the South China Sea, Regional Cooperation and Development” to find a way to cooperate, so there is a basis for their cooperation. We, therefore, consider these three countries as an example to illustrate the Blue Carbon cooperation and its distribution.

*5.2 Data of inputs in Blue Carbon cooperation*

According to Yue [18], China has been at the forefront of the world in the field of Blue Carbon research. A theoretical framework of the marine micro-biological carbon pump [19], proposed by a team led by the Chinese Academy of Sciences, Jiao Nianzhi, can explain the huge dissolved organic carbon pool of the ocean (new Blue Carbon). It has received wide attention and recognition among international counterparts. As a leading theoretical framework in the world, the marine micro-bio-carbon pump has been reported by top magazines such as Nature [19]. Therefore, we set the Chinese Blue Carbon technology level as A1=1, and the Indonesian and Thai Blue Carbon technology levels assumed to be A2=A3=0.5, respectively, as an example.

To simplify the model, we only consider mangroves, seagrass beds and salt marshes as Blue Carbon resource, according to the 2016 data, the average carbon burial rate of mangroves is 226g C m-2 a-1, and for seagrass beds it is 138g C m-2 a-1, while for salt marshes, it is 218g C m-2 a-1 [20]. Base on the magnitude of their average carbon burial rates, the contribution rate of mangroves to Blue Carbon ecosystems per unit area is set to be 1, and for the seagrass beds and the salt marshes, the rates are 0.61 and 0.96, respectively.

In China, the area of mangroves is 328.34 km2, the area of seagrass beds is 87.65 km2, and the area of salt marshes is 1207-3434 km2 (using the average value- 2320.5 km2) [20]. The effective use area for China's Blue Carbon ecosystem is hence X1=328.34+87.65\*0.61+2320.5\*0.96=2609.49 km2.

According to the distribution map of the salt marsh world drawn by Mcowen *et al.* [21], Indonesia, Thailand, and other countries have no obvious salt marshes. By the 2016 data, Indonesia has a mangrove area of 31,894 km2 and a seagrass bed area of 30,000 km2 [3]. The effective use area for the Indonesian Blue Carbon ecosystem is, therefore, X2=31,894+30,000\*0.61=50,194 km2. Similarly, by the 2013 data [22], the area of mangrove forest in Thailand is 2296.19 km2, the area of seagrass bed is 189.86 km2 [23]. The effective use area of the Thailand Blue Carbon ecosystem is X3=2296.19+189.86\*0.61=2412 km2.

Furthermore, according to the World Bank website[[9]](#footnote-9), China's GDP in 2017 was 12,237,700.48 million 2017 US dollars, Indonesia's GDP was 1,015,420.59 million 2017 US dollars, and Thailand's GDP was 455,302.68 million 2017 US dollars. In order to maintain dimensional consistency, we assume that the initial capital of each country that can be invested is one percent of their GDP; that is Y1=122,377 million 2017 US dollars, Y2=10,154 million 2017 US dollars, and Y3=4,553 million 2017 US dollars. Table 1 provides a summary of the inputs.

**--- Insert Table 1 About Here ---**

*5.3 Comparison of different results between cooperation and non-cooperation*

From our analyses in section 3.4 and 4.2, it can be seen that the feasibility of Blue Carbon cooperation (i.e. total value obtained from cooperation is greater than or equal to that from non-cooperation) and the individual rational[[10]](#footnote-10) property of Shapley value exists for all α∈(0,1), thus in this example, for simplification of the calculation, the output elasticity of capital α is assumed to be 0.5.

Firstly, we calculate payoffs from non-cooperative Blue Carbon for each country:

V1=A1X10.5Y10.5≈17,870

V2=A2\*X20.5Y20.5≈11,288

V3=A3\*X30.5Y30.5≈1,657

Then we calculate payoffs from cooperative Blue Carbon activities:

V(1,2)=83,655

V(1.3)=13,908

V(2,3)=25,246

V(1,2,3)=87,001

Where V(*i, j*) denotes the payoff from cooperation of country *i* and *j*, *i*≠*j*, *i*, *j*∈(1,2,3); V(1,2,3) denotes the payoff from the grand coalition.

We only consider the allocation for grand coalition here:

See Table 2 for calculating the Shapley value in a grand coalition for China as follows.

**--- Insert Table 2 About Here ---**

Employ the formula in section 4.1 to calculate the Shapley value:
$$∅\_{i}\left(v\right)=\sum\_{S⊂I}^{}\frac{\left(\left|S\right|-1\right)!\left(n-\left|S\right|\right)!}{n!}\left[v\left(S\right)-v\left(S\i\right)\right], i=1,2,…n$$

The result indicates that $∅\_{1}\left(v\right)$=46,314

Applying the same method, $∅\_{2}\left(v\right)$=37,353, $∅\_{3}\left(v\right)$=3,334.

Then it can be observed that: V(1,2,3)= 87,001>V1+V2+V3=30,815

$∅\_{1}\left(v\right)$=46,314>V1=17,870,

$∅\_{2}\left(v\right)$=37,353>V2=11,288,

$∅\_{3}\left(v\right)$=3,334>V3=1,657.

It can be seen from the above results that the Blue Carbon cooperation between China, Indonesia, and Thailand is feasible since the value generated from their cooperation is much higher than the sum value from their own development. Moreover, the distribution using the Shapley value is individually rational as all three countries can receive a higher benefit than they could obtain without cooperation. It is suggested that these counties in the SCSR who have close connections and abundant Blue Carbon resources should establish a cooperative mechanism in the Blue Carbon development as soon as possible in order to make joint efforts to protect our planet.

**6. Conclusions and discussions**

*6.1 Conclusions*

1) The theoretical formula for the cooperative game proves that the Blue Carbon cooperation of the countries in the SCSR is feasible. From the mathematics proof in section 3.4, it can be concluded that the total value obtained from cooperation is greater than or equal to the total value from non-cooperation no matter how many countries participated in the cooperation. Therefore, Blue Carbon cooperation is profitable and thus feasible, countries should form a cooperative relationship in Blue Carbon since it can better increase carbon absorption and thus better curb climate change for all human being.

2) The allocation of Blue Carbon using Shapley value is acceptable, which means Blue Carbon cooperative relationship is sustainable. From the analysis in section 4, we can see that the participant is proved to be individual rational, which means each participant receive higher or equal payoff than it can obtain without cooperation, countries would be satisfied with the allocation after their cooperation and hence would like to continue this relationship in the long term.

3) There are significant differences in Blue Carbon technology and Blue Carbon resource among countries in the SCSR, thus cooperation can integrate countries’ technologies and then develop Blue Carbon more efficiently. From our example, it can be seen that countries in SCSR have different development levels in Blue Carbon, some countries do on have advanced technology to protect or recover the Blue Carbon area efficiently, with the cooperation, technologies can be shared by participants, hence countries can develop more evenly in this global activity.

*6.2 Theoretical contributions*

We developed the following contributions to the existing theory on Blue Carbon management:

1) The “SCSR” is the region with the most abundant distribution of global Blue Carbon resources and the economic cooperation of countries in this region can make extensive contributions to the solution of global climate issues. The theoretical proof of the feasibility of Blue Carbon Cooperation in this article can provide a theoretical basis and guidance for the formulation of international Blue Carbon cooperation measures.

2) The increase in the number of participating countries in the Blue Carbon cooperative game model does not affect existing cooperation solutions. It is theoretically proved that Blue Carbon cooperation can expand from the SCSR to the world. This also confirms that the proposal "Building a global community of marine destiny" put forward by Chinese President Xi Jinping is realistic from a perspective of economic theory.

3) The theoretical model reveals that the more capital and technology inputs, the easier it is to generate economies of scale; the higher income the Blue Carbon alliance can distribute, the more the countries concerned are willing to choose the cooperation strategy and join the alliance; it theoretically indicates the focus areas and directions of the Blue Carbon international cooperation.

4) The production of Blue Carbon is a coordinated process of land and sea. Countries without coastlines can also improve the efficiency of Blue Carbon production by controlling the eutrophic components of rivers entering the sea. At the same time, the high seas are also important areas for Blue Carbon sequestration and carbon sinks. In theory, the economic activity of Blue Carbon development is a global process of cooperation that requires the participation of countries all over the world.

*6.3 Practical aspects*

From the perspective of economic game theory, the Blue Carbon cooperation in the SCSR is realistic. Cooperative economic measures can effectively promote international cooperation of Blue Carbon, promote economic integration, and maintain peace and prosperity in the SCSR.

Firstly, the carbon trading market is one of the important ways for the countries in the SCSR to obtain economic benefits. They need to integrate the carbon trading markets of relevant countries and negotiate unified standards for carbon measurement, carbon trading, and carbon tariffs. The completed trading market can help countries trade carbon emissions at low cost and obtain carbon sink revenue.

Secondly, the dissemination and sharing of Blue Carbon advanced technologies are the most important ways to increase carbon sinks and it is also a realistic way to promote active cooperative action among countries in the region. They can collaborate in the fields of developing fish farming technology, ocean carbon measurement, deep-sea resource development, marine remote sensing measurement, marine digital industrial technology and promote the dissemination and sharing of Blue Carbon technology through multi-channel, multi-level and multi-field technical cooperation, thereby increasing the amount of carbon sinks in the SCSR. It can protect the interests of the countries' economies and the ecological environment through the rational Blue Carbon resource allocation mechanism and then promote the construction of the marine destiny community in the SCSR.

Finally, finance and digital technologies are the blood of economic development in the 21st century and have a realistic value for the development of the Blue Carbon economy. Based on the use of the “Asian Investment Bank” and the “Asian Development Bank”, countries in the SCSR can combine digitalized blockchain technology, integrate the carbon trading market, establish the Asian Blue Carbon blockchain financial institutions, and raise funds for the development of the Blue Carbon industry through new specialized international financial institutions, thereby increasing the Blue Carbon capital investment in the SCSR and increasing the carbon sink income within the region. It could provide demonstration projects for global climate governance.

*6.4 Research limitations and future research*

1) The countries in the SCSR have close relationships in economy, trade, politics, and culture, and have become a network system of interaction and influence. In the process of constructing our model, the rational economic man is assumed for simplifying the relationship between countries. In future research, the model of the cooperative game will be revised, based on actual political and economic networks.

2) After the carbon trading market is established, the price of Blue Carbon will change with the structure of supply and demand. The Blue Carbon economic income distribution of countries in the SCSR will affect the choice of game strategy. Our model is built on the Douglas production function and does not reflect the cost of Blue Carbon development and spillover effects. Subsequent research will consider the opportunity cost of losing alternative ecosystem development and other factors.

3) Limited by the Blue Carbon data resources, our article only selects the data of three countries for empirical testing, data should be increased in the follow-up research, and the certification process should be improved by increasing the number of countries and empirical data.

4) Due to the lack of data, this article has not tested the goodness of fit in the model used; further research can take into account the empirical payoff of Blue Carbon development, represented by the Blue Carbon credits, and then test the goodness of fit of our Blue Carbon production model.

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1. The SCSR includes the states and territories with borders on the sea: the People's Republic of China, the Philippines, Malaysia, Brunei, Indonesia, Thailand, Singapore and Vietnam. [↑](#footnote-ref-1)
2. Blue carbon is subdivided into oceanic and coastal blue carbon component. Within this article the term blue carbon is applied only to coastal blue carbon, the carbon stored in mangroves, tidal marshes and seagrass meadows. [↑](#footnote-ref-2)
3. Association of Southeast Asian Nations [↑](#footnote-ref-3)
4. UNEP: United Nations Environment Programme; FAO: Food and Agriculture Organization; UNESCO: United Nations Educational, Scientific and Cultural Organization; IOC: Intergovernmental Oceanographic Commission. [↑](#footnote-ref-4)
5. Partnerships in Environmental Management for the Seas of East Asia [1]. [↑](#footnote-ref-5)
6. A participant is Individual rational means that a participant will not agree to receive money less than that the agent could obtain without coalition, that is, *xi*≥*v(i)* [12]. [↑](#footnote-ref-6)
7. In mathematics, a sequence {an}, n≥1, is called super-additive if it satisfies the inequality: am+n ≥ am + an, m≥1, n≥1 [17]. [↑](#footnote-ref-7)
8. Since Amax$ (\sum\_{i}^{n}X\_{i})$α ($\sum\_{i}^{n}Y\_{i})$1-α≥$\sum\_{i}^{n}($AiXiαYi1-α), for any m,n≥1, am+n=Amax$ (\sum\_{i}^{m+n}X\_{i})$α ($\sum\_{i}^{m+n}Y\_{i})$1-α≥am+an$=\sum\_{i}^{m+n}($AiXiαYi1-α). [↑](#footnote-ref-8)
9. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD [↑](#footnote-ref-9)
10. A participant is Individual rational means that a participant will not agree to receive money less than that the agent could obtain without coalition, that is, *xi*≥*v(i)* [12]. [↑](#footnote-ref-10)