

Article

Enhancing Eco-Efficiency of Agro-Products' Closed-Loop Supply Chain under the Belt and Road Initiatives: A System Dynamics Approach

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Abstract: This study redesigns the supply chain of agricultural products in southwest China under the Belt and Road Initiative to improve its eco-efficiency by considering the associated agro-wastes flowing into bioenergy enterprise for energy production. Two scenarios are created, in which the first assumes that all waste flows into the enterprise, whereas the second only considers the inflow of agro-waste produced by farmers and the wholesale market. A system dynamics simulation is conducted by using carbon emissions per product as an indicator to obtain the optimal scenario for managerial practice and design an incentivizing mechanism to drive supply chain operations. A case study is provided to demonstrate application of the system dynamics. Finally, the limitations of the study are discussed to lay the foundation for further improvement.

Keywords: supply chain management; eco-efficiency; closed-loop; system dynamics; agro-products

1. Introduction

Since its launch in 2013, the Belt and Road Initiative has been emphasizing green cooperation among the involved countries to highlight low carbon characteristics of the domestic and overseas supply chain and enhance the value added to products [1,2]. Most countries involved in this initiative are emerging and developing economic entities, where agriculture is a leading industry in their national economies [3]. Nevertheless, their agro-product supply chains usually have low eco-efficiencies, which leads to less utilization of agro-waste, thus having an impact on the formulation of reverse logistics [4,5]. As these agro-wastes generally contain large amounts of biomasses, recycling them for energy recovery may yield greater economic and environmental benefits [6–8]. However, the incorporation of bioenergy enterprises into the supply chain inevitably disturbs supply chain operations. For instance, it may increase the number of stakeholders involved, hence complicating the coordination of the supply chain network [9]. Meanwhile, additional costs including the cost of agro-waste collection, pretreatment, and transportation may be incurred, causing an impact on the value added to the supply chain [10,11].

This study aims at redesigning the conventional agro-product supply chain to improve its eco-efficiency by considering the associated agro-waste flowing into bioenergy enterprise for energy production. Two operations scenarios are established, using system dynamics simulation to select

the optimal scenario to enhance eco-efficiency for the proposed supply chain. In addition, an optimal policy mechanism is developed to put the optimal scenario into supply chain management practice, thus enhancing its sustainability. There are three contributions within this study: first, this study takes the concept of sustainability into account for the agro-product supply chain with consideration to its eco-efficiency; second, system dynamics enable us to offer a visual analysis for agribusinesses to realize their critical processes; third, the analytical results provide the evidence to guide agribusiness in improving their current performance toward sustainability under the Belt and Road Initiatives.

The remaining parts of this study are organized as follows: Section 2 presents the literature reviews. Section 3 presents the method conceptualization and formulation. Results are discussed in Section 4. Section 5 addresses the implications. Lastly, conclusions and research limitations are expressed in Section 6.

2. Theoretical Background

Conventional optimization of the agro-product supply chain focuses on how to increase the economic benefits. Xiao et al. [12] applied the CIF (Cost Insurance and Freight) business model to investigate the impacts of transport delay, price, and freshness of agro-products on the supply chain, consequently devising a cost-sharing mechanism to enhance its associated economic benefits. Pathumnakul et al. [13] further considered the factors of technical maturity and seasonal market demands, in turn optimizing the supply chain of fresh shrimps in Thailand to minimize the storage cost. With regard to uncertainties in productivity, Bohle et al. [14] applied robust optimization to the supply chain of wine grapes and developed an optimal grape harvesting scheduling. Similarly, Paksoy et al. [15] considered production, transport capacity, and the uncertainties in market demand to optimize the edible vegetable oil supply chain. Owing to the perishable nature of agro-products, De Keizer et al. [16] combined multi-objective optimization and discrete event simulation to redesign the supply chain and reduce the financial risk. Soto-Silva et al. [17] further optimized the coordination mechanism of the agro-product supply chain to mitigate the decay of agro-products.

With the emergence of low-carbon agriculture, carbon emissions have been gradually incorporated into the decision-making and optimization of the agro-product supply chain as an important indicator to enhance eco-efficiency. Soysal et al. [18] used a beef supply chain as an example to investigate the influences of road structure, vehicle and fuel types, weight loads of vehicles, and traveled distances on the carbon emissions of the supply chain. Similar studies were conducted by Accorsi et al. [19] and Chandrasekaran et al. [20], who aimed to minimize carbon emissions during logistic processes to optimize the logistics network structure of the potato supply chain. On the other hand, Jonker et al. [21] shed light on the greenhouse gas (GHG) emission intensity of the biomass supply chain of sugarcane ethanol production by optimizing the sizes and locations of enterprises. Meanwhile, Miranda-Ackerman and Azzaro-Pantel [22] incorporated the net present value (NPV) and investment (I), global warming potential (GWP), and average variable unit cost (AVUC) as the objective functions to construct a multi-objective model, revising the location, allocation of resources, and production capacity of the supply chain of orange juice production.

In recent years, the agro-product supply chain has inclined toward a closed-loop transition (i.e., optimization based upon a lifecycle assessment) to reinforce its sustainability [23]. Using the closed-loop tangerine supply chain of a Korean brand, Kim et al. [24] designed the optimal structure of the closed-loop supply chain based upon returnable transport items (RTIs). Similarly, Turki et al. [25] optimized a closed-loop supply chain, by taking a combination of manufacturing, remanufacturing, transport, and warehousing into account. Zabaniotou et al. [26] discussed the example of the closed-loop supply chain of small-scale olive oil production and proposed a symbiosis approach to transform waste into energy sources. Banasik et al. [27] constructed a closed-loop supply chain of the mushroom industry and optimized the cost and environmental impact of mushroom cultivation through a multi-objective model.

Since most of the above studies targeted optimizing the network of an existing supply chain structure, they lacked a comparison among different supply chain operation patterns and discussion on the policy design postoptimization. Therefore, this study adopts system dynamics modeling and proposes different operational scenarios of the agro-product supply chain to select the optimal scenario based upon carbon emissions per unit product. This is followed by a discussion on the incentive policies to facilitate the operation of the optimal scenario.

3. Method

3.1. Model Conceptualization

A simplified agro-product supply chain comprises farmers, market, consumers, and a municipal waste disposal center. Farmers are mainly responsible for agricultural production. The “market” indicates a retailer of a large-scale wholesale market, who purchases agro-products at a market price and sell them to the consumers (i.e., urban residents). The agro-wastes from the farmers, retailers, and consumers are sent to the municipal landfill for ultimate disposal. Due to bringing bioenergy enterprises into the supply chain network, agro-wastes may be recovered for energy production. Their power generation is merged into the local grid system to provide renewable energy consumed by urban residents (consumers) and farmers, to reduce waste disposal in landfills and promote energy savings.

To explore the optimal pattern for supply chain operations against this background, two scenarios are fabricated in this study: in Supply Chain 1, all the agro-wastes produced by farmers, market, and consumers proceed to the bioenergy enterprise for processing as shown in Figure 1a; in Supply Chain 2, agro-wastes produced by consumers are sent to the landfill, whereas the wastes produced by farmers and the market enter the bioenergy enterprise as shown in Figure 1b. Compared with Scenario 1, the latter is set based upon possible complexities involved in waste classification and pretreatment because of consumers’ individual rationalities which may result in less efficiency in agro-waste collection.

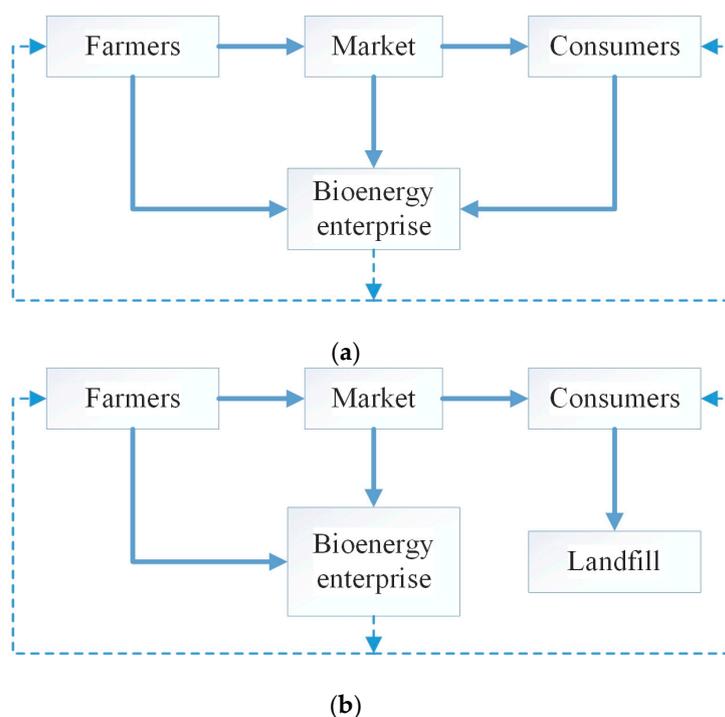


Figure 1. Scenarios of the redesigned supply chain network. (a) Scenario 1 of the redesigned supply chain; (b) Scenario 2 of the redesigned supply chain.

The modeling process usually entails four basic steps: structural analysis of the system, causal loop diagram drawing, stock and flow diagram drafting, and model validation [28,29]. To determine the key factors of the system and grasp their interrelations, the following hypotheses regarding the supply chain design are proposed:

1. The prices of the same product do not vary significantly in different commercial regions;
2. The locations of the farms and the market as well as the logistic routes between different supply chain nodes are relatively stable;
3. The supply chain only concerns the mobility of a single type of product.

3.2. Model Formulation

A casual loop diagram is drawn to illustrate the system structure and the interrelation among key factors. In Figure 2, there are two reinforcing loops and three balancing loops. The first reinforcing loop shows the increase in agro-wastes and the consequent increase in total agro-wastes due to increased market acquisition, which leads to a higher production of biomass energy and a lower consumption of traditional energies; this reduces the supply cost and eventually encourages more market acquisition. As for the second reinforcing loop, the increased production of agro-products leads to more agro-wastes and more total wastes; this stimulates biomass energy production and lowers the farmers' consumption of traditional energies, in turn reducing the supply cost and expanding the production of agro-products.

In terms of the balancing loops, the first pertains to the increased energy consumption caused by increased market acquisitions; this results in greater energy use and higher overall cost of the supply chain, in turn shrinking the amount of market acquisitions. The second balancing loop examines the decreased stock of agro-products due to increased market acquisitions, followed by a reduced production of agro-wastes and, thus, biomass energy; as a result, the use of traditional energy increases, increasing the overall cost and, eventually, lowering the number of market acquisitions. The last balancing loop is about the increase in the stock of agro-products due to increased market acquisitions; this leads to the increased use of traditional energies and then a higher supply cost, reducing the market acquisitions.

Based on the above analyses, two-feedback-loop clusters are defined as follows:

Reinforcing loop clusters: Marketing acquisition → Marketing waste generation → Total waste generation → Recycling amount of bioenergy plant → Conventional energy consumption → Cost of energy use → Marketing acquisition; Farmers' agro-production → Waste generation in farming stage → Total waste generation → Recycling amount of bioenergy plant → Conventional energy consumption → Cost of energy use → Farmers' agro-production.

Balancing loop clusters: Marketing acquisition → Stock in farmers' agro-production → Waste generation in farming stage → Total waste generation → Recycling amount of bioenergy plant → Conventional energy consumption → Cost of energy use → Marketing acquisition; Marketing acquisition → Energy consumption in Marketing acquisition → Conventional energy consumption → Cost of energy use → Marketing acquisition; Marketing acquisition → Stock of agro-products in marketing stage → Conventional energy consumption → Cost of energy use → Marketing acquisition.

With reference to the causal loop diagram, this study adopts Vensim 6.0 to compose a stock and flow diagram to quantify the interrelation among the key variables as shown in Figure 3. These variables can be divided into three groups: state, rate, and auxiliary variables. State variables are factors that are cumulative over time [29], such as the inventory of agro-products. Rate variables are integrals representing the difference between the input and output rates with respect to time [29]. An example is the integral difference between the stock of agro-products plus the rate of agro-product production and the rate of market acquisition. Auxiliary variables are the intermediates between state and rate variables [29]. An example is the variance of carbon emissions. All variables used in

Table 1. Key variables of the system dynamics (SD) model.

Key Variable	Variable Type	Input/Output
C (Cost)	Constant	Input
FECFS (Factor of Energy Consumption in Farming Stage)	Constant	Input
FECT (Factor of Energy Consumption in Transportation)	Constant	Input
FECMS (Factor of Energy Consumption in Marketing Stage)	Constant	Input
FECCE (Factor of Energy Consumption Converted into Carbon Emissions)	Constant	Input
CEFL (Carbon Emissions Factor of Landfill Disposal)	Constant	Input
BCF (Biomass-to-Energy Conversion Factor)	Constant	Input
TCEF (Factor of Carbon Emissions in Transportation)	Constant	Input
PLRF (Product Loss Rate in Farming Stage)	Rate	Input
PLRM (Product Loss Rate in Marketing Stage)	Rate	Input
PLRC (Product Loss Rate of Consuming Stage)	Rate	Input
IPA (Initial Production of Agro-Products)	Constant	Input
FMR (Factor of Marketing Revenue)	Constant	Input
AP (Acquisition Price)	Constant	Input
MP (Marketing Price)	Constant	Input
PIFS (Product Inventory in Farming Stage)	State	Output
PIMS (Product Inventory in Marketing Stage)	State	Output
PICS (Product Inventory in Consuming Stage)	State	Output
AL (Amount of Landfill Disposal)	State	Output
TAP (Total Amount of Products)	State	Output
TCE (Total Carbon Emissions)	State	Output
TRF (Total Revenue of Farmers)	State	Output
RABP (Recycling Amount of Bioenergy Plant)	State	Output
ECRL (Energy Consumption of Reverse Logistics)	State	Output
TEC (Total Energy Consumption)	State	Output
VECT (Variation of Energy Consumption in Transportation)	Auxiliary	Output
VECF (Variation of Energy Consumption in Farming Stage)	Auxiliary	Output
VECM (Variation of Energy Consumption in Marketing Stage)	Auxiliary	Output
CEP (Carbon Emissions Per Product)	Auxiliary	Output
PP (Profit Per Product)	Auxiliary	Output
MR (Market Revenue)	Auxiliary	Output
FII (Farmers' Income Index)	Auxiliary	Output
FFI (Factor of Farmers' Income)	Auxiliary	Output
FMP (Factor for Marketing Price)	Auxiliary	Output
FCD (Factor of Consumers' Demand)	Auxiliary	Output
VFP (Variation of Farmers' Production)	Auxiliary	Output
VMA (Variation of Marketing Acquisition)	Auxiliary	Output
VCP (Variation of Consumers' Purchasing)	Auxiliary	Output
VC (Variation Consumption)	Auxiliary	Output
VFI (Variation of Farmers' Income)	Auxiliary	Output
VP (Variation of Total Products)	Auxiliary	Output
VCE (Variation of Carbon Emissions)	Auxiliary	Output
VWRBP (Variation of Waste Recycling by Bioenergy Plant)	Auxiliary	Output
VCEWT (Variation of Carbon Emissions in Waste Transportation)	Auxiliary	Output
VCET (Variation of Carbon Emissions in Transportation)	Auxiliary	Output
VARF (Variation of Agro-Waste Recycling from Farmers)	Auxiliary	Output
VWRM (Variation of Waste Recycling from Market)	Auxiliary	Output
VCEL (Variation of Carbon Emissions in Landfill Disposal)	Auxiliary	Output
VWGC (Variation of Waste Generation in Consuming Stage)	Auxiliary	Output
VBP (Variation of Bioenergy Production)	Auxiliary	Output
CELD (Carbon Emissions of Landfill Disposal)	Auxiliary	Output
VECRL (Variation of Energy Consumption of Reverse Logistics)	Auxiliary	Output
VEC (Variation of Energy Consumption)	Auxiliary	Output

4. Results and Discussions

4.1. Case Background

This study uses yellow chives, which are often seen in southwest China, as typical agro-products for our case study. Due to substantial market demand, an industrial pattern of large-scale chive

production has been established. The supply chain comprises a production base, a large-scale wholesale market of agro-products, main consuming towns in the neighborhood, a landfill for household waste, and a bioenergy enterprise. Their geographical locations are illustrated in Figure 4. The production base of the yellow chives is the biggest in southwest China, located in the city of Chengdu in the Sichuan province, and produces more than 8000 tons annually with a sales volume of approximately 16 million RMB and a damage rate of around 20–30%. The damaged produce is transported to a nearby landfill that processes urban household wastes. As the concept of green supply chain management is put into practice, the agro-wastes from the production base are integrated with the surrounding bioenergy enterprises to enhance the utilization of agro-waste and reduce energy consumption.

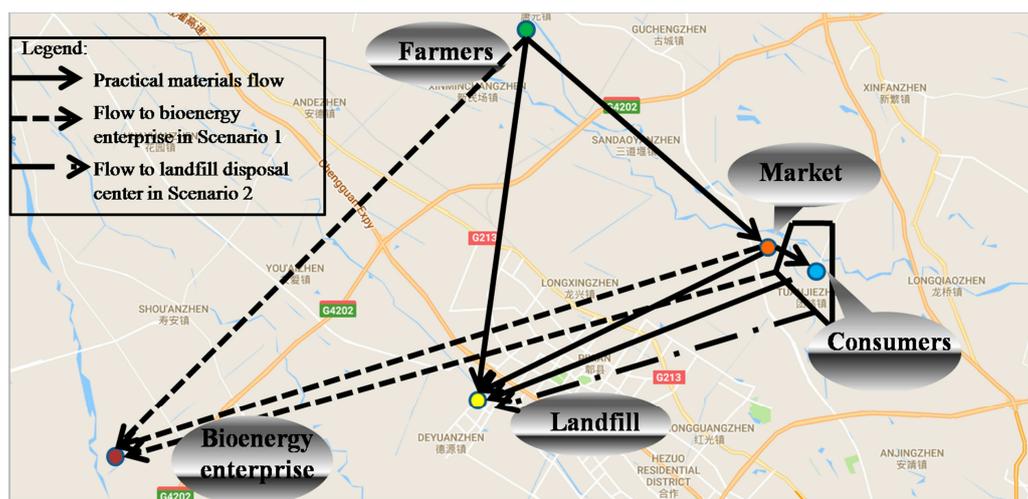


Figure 4. Geographical locations of the Case Study.

The data in this study is mainly collected through field investigation and review of related statistics. Two types of parameters are involved in the model. The first involves quantifiable, determinable parameters obtained either through investigation, such as the market price of yellow chives, or from previous literature, such as the carbon emissions of supply chain activities. The other group contains parameters that are difficult to quantify, such as the influences of income and the damage rates of agro-products at different stages of the supply chain, which are mainly obtained by the Delphi method and interviews with experts. The detailed parameters are listed in Table 2.

Table 2. Measurements of the model input.

Variable	Value	Source
Cost (C)	0.72 Yuan/kg	Field investigation
FECFS (Factor of Energy Consumption in Farming Stage)	0.0018 kg diesel/(kg·day)	Field investigation
FECMS (Factor of Energy Consumption in Marketing Stage)	0.0044 kg diesel/(kg·day)	Field investigation
FECCE (Factor of Energy Consumption Converted into Carbon Emissions)	3.1388	IPCC [30]
TCEF (Factor of Carbon Emissions in Transportation)	0.0347 kg CO ₂ /kg·100 km	Patel and Kumar [31]
PLRC (Products Loss Rate of Consuming Stage)	0.3	Delphi method
FECT (Factor of Energy Consumption in Transportation)	0.011 kg diesel/kg·100 km	Giordano et al. [32]
CEFL (Carbon Emissions Factor of Landfill Disposal)	0.2708 kg CO ₂ /kg waste	Lee et al. [33]
BCF (Biomass-to-Energy Conversion Factor)	0.007 kg diesel/kg recycled waste	AI-Hamamre et al. [8]
PLRF (Products Loss Rate in Farming Stage)	0.25	Delphi method
PLRM (Products Loss Rate in Marketing Stage)	0.1	Delphi method

4.2. Model Validation

Prior to the system dynamics simulation, it is necessary to validate the constructed model to test its effectiveness in reflecting reality. There are typically two typical methods to ensure the model accuracy, i.e., behavior sensitivity analysis and historical data comparison, to verify the extent to which the model is consistent with the actual situation [34,35]. In this study, the latter is used to test the model

performance, through comparing the discrepancies between the simulated and actual values through error analysis of the model, in turn quantifying the accuracy of the model. The common practice is to check whether the simulation result of a certain quantitative variable is in accordance with the corresponding historical data, e.g., the total income of farmers. The simulation result is compared against the actual statistics of the farmers' income in the past few years. Table 3 reflects the differences between the simulation results and the historical statistics for the past seven years, for which the average relative error is shown as 3.93%. The error is considered within 15%, which validates the reliability of the presented model [36].

Table 3. Comparison of simulated and historical values of farmers' income.

Farmers' Income	2010	2011	2012	2013	2014	2015	2016
	(Ten Thousand Yuan)						
Simulation result	206.79	220.01	206.19	221.34	216.33	220.48	217.23
Statistical data	205.12	214.32	220.67	212.83	230.59	225.34	229.03
Relative error	0.81%	2.65%	6.56%	4.00%	6.18%	2.16%	5.15%

4.3. Benchmark Scenario

In the benchmark scenario, the bioenergy enterprises are excluded from the supply chain activities, and all the agro-wastes are delivered to the landfill that processes urban household wastes. Using 10 years as one simulation cycle, the simulation results of the carbon emissions per unit product in the benchmark scenario are shown in Figure 5.

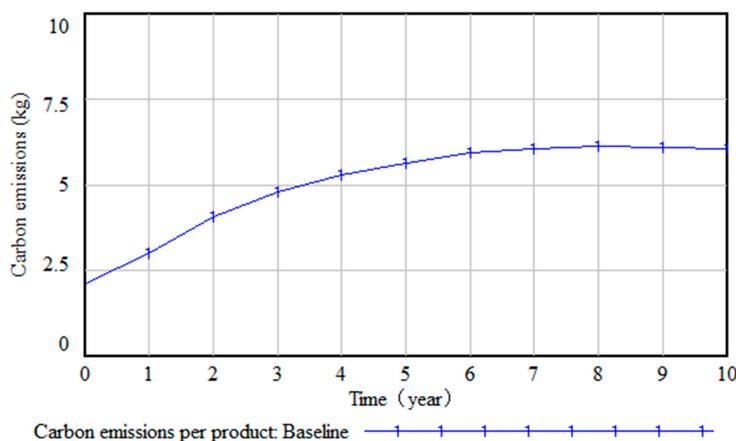


Figure 5. Carbon emissions per unit product in the benchmark scenario.

4.4. Scenario Selection

Figure 6 reflects the simulation results of the carbon emissions per unit agro-product under the two proposed scenarios. Compared with the benchmark scenario, both scenarios exhibit a significant decline of carbon emissions during the simulation cycle. Scenario 1 produces a cumulative decrease of 14.13%, whereas Scenario 2 shows a cumulative decrease of 18.02%. It is evident that Scenario 2 is more effective in reducing carbon emissions. This conclusion indicates that although recycling and processing agro-wastes generates a greater amount of bioenergy, this approach is undesirable because the dispersion of consumers contributes to an increase in carbon emissions during waste collection and transport and, consequently, an increase in total emissions.

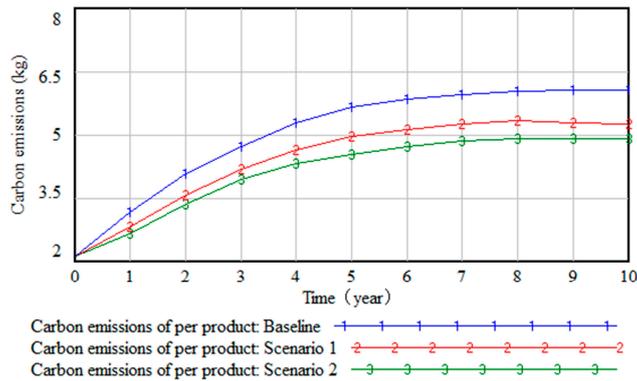


Figure 6. Carbon emissions per unit product under two scenarios.

4.5. Development of Incentive Policies

The above analysis shows that, despite the substantial environmental benefits brought about by a green supply chain, the energy production of the bioenergy enterprises is relatively small due to external costs produced by measures for energy savings and emission reductions. The wide dispersion of the agro-wastes leads to high costs of waste collection and logistics, which cripple the management and implementation of the agro-product supply chain. Under this context, government measures such as subsidies, green procurement, and tax incentives serve an important role in maintaining the stable operations of a green supply chain. Given that Scenario 2 has been chosen as the preferred operation mode, this section identifies the optimal incentive mechanism by observing how government subsidies influence the emissions reduction of the supply chain.

4.5.1. Government Subsidies for Bioenergy Enterprise

Government investments and subsidies are effective in helping bioenergy enterprises improve their operations and development [37]. This study assumes that, after subsidization, the bioenergy enterprises will be able to choose a high-cost cleaner production plan to boost their energy conversion efficiency to three times the original. Under such a context, the simulation results indicate an insignificant drop in carbon emissions per unit product of 6.05%, as shown in Figure 7.

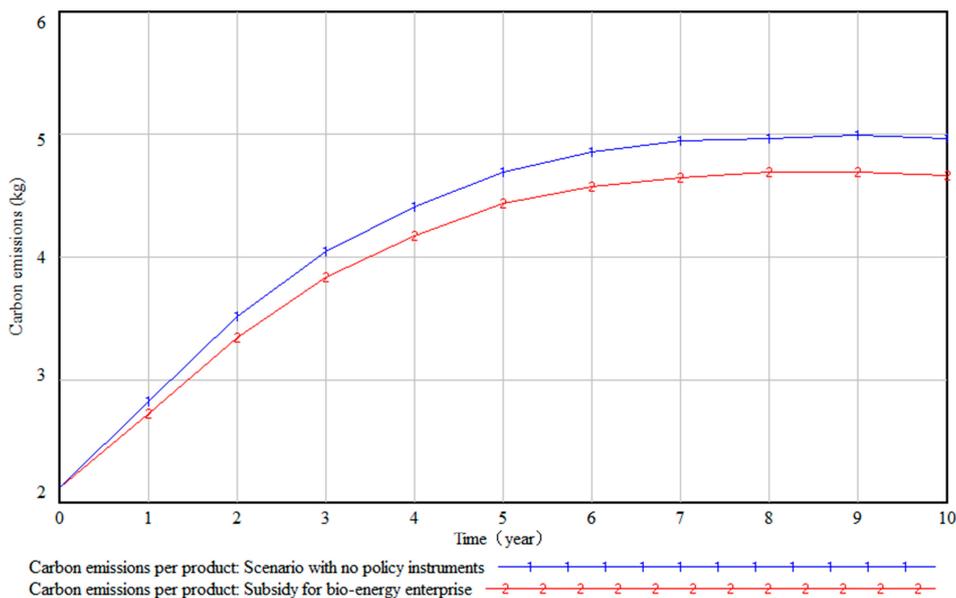


Figure 7. Carbon emissions per unit product under subsidization of bioenergy enterprises.

4.5.2. Logistic Subsidies

In this scenario, the government considers subsidizing logistics to stimulate the transport processes in the supply chain to shift from fossil energy driven to renewable energy driven. According to Figure 8, the carbon emissions per unit product in this scenario decline by 11.29%. Compared with subsidizing the bioenergy enterprises, logistic subsidies have significantly more economic and environmental benefits. Therefore, any attempt to optimize the agro-product supply chain may give priority to emissions reduction at the logistic stages.

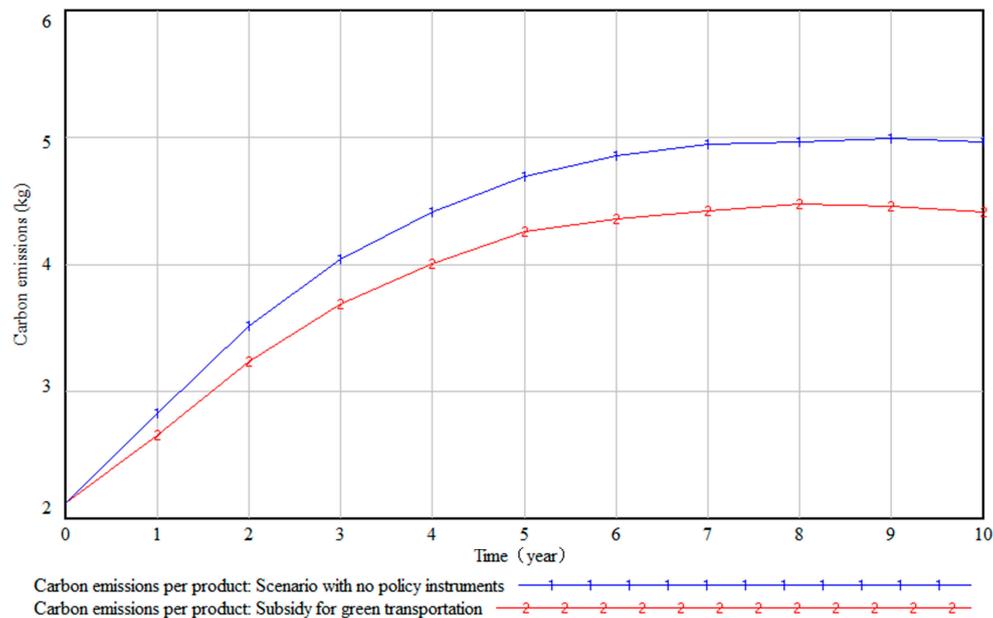


Figure 8. Carbon emissions per unit product under logistic subsidization.

5. Implications

The case example is used to demonstrate the application of system dynamics, which is employed to select an operations scenario for supply chain management practice to enhance its eco-efficiency, by using carbon emissions per unit product as the indicator for simulation. The results also provide insight into improvement of agro-product supply chain management of countries along the Belt and Road routes. For instance, subsidizing the logistic processes can effectively lower emission intensity. This is also an indirect proof that the carbon emissions of the agro-product supply chain largely originate from the logistic processes [38]. In comparison, subsidizing bioenergy enterprise is ineffective in terms of emission reduction. This finding indirectly verifies the research conclusion by Yue et al. [39], who state that the lack of a systematic coordination mechanism within bioenergy enterprises has hindered their electricity generation capacity and industrial scale, in turn limiting the benefits of introducing high-efficiency energy conversion technologies for reducing carbon emissions. Therefore, we suggest that sufficient consideration should be given to the coordination and balance among stakeholders of a supply chain, while bioenergy enterprises should be industrialized and expanded to a certain scale to gradually highlight their market competitiveness and eco-efficiency.

There are several uncertainties in this study. First, choosing different types of supply chains during the case study to analyze emissions reduction policies often leads to varying conclusions. For instance, this study examines the supply chain of typical agro-products, represented by yellow chives, and concludes that subsidies are best provided to logistic processes for emissions reduction. However, during the study by Smith et al. [40] on the supply chain of a bioenergy generated by anaerobic fermentation in Africa, it was found that government subsidies should most preferably cover some of the investments in related infrastructure development. Moreira et al. [41] used the

ethanol supply chain in Brazil as an example and argued that the optimal government policy for emissions reduction is to pay both upstream and downstream industries a subsidy of \$10 USD per ton of carbon dioxide reduction. It is evident that different types of supply chains require different policies on emissions reduction. Second, the system boundaries also create uncertainties in the computation of carbon emissions. For example, in terms of electricity consumption, this study merely focuses on direct consumption, without further considering the indirect carbon emissions from secondary energy consumption by using electricity. In addition, the agro-product supply chain is highly uncertain and involves interaction among stakeholders. In particular, consumers' preferences and needs have yet to be effectively predicted. Whether government subsidies for bioenergy enterprises will result in rent-seeking behavior and dependence on the subsidies is yet to be examined.

6. Conclusions

Against the strategic background of the Belt and Road Initiative, this study redesigned a regional agro-product supply chain by taking bioenergy enterprises into account to reduce agro-wastes and enhance eco-efficiency. Two operational scenarios were created, in which Scenario 1 assumes that all the agro-waste flows into the bioenergy enterprise, whilst Scenario 2 only takes the agro-wastes produced by farmers and the wholesale market for energy production into account.

System dynamics offer a powerful tool to select the optimal scenario to enhance the eco-efficiency of the proposed supply chain. The simulation result shows that Scenario 2 has greater potential in improvement of the eco-efficiency of the agro-product supply chain, particularly reflected in its carbon emission reduction.

In order to drive such a scenario into management practice, an incentivizing mechanism was designed based upon governmental subsidy for the bioenergy enterprise or the logistic processes. The simulation result shows that subsidy for the logistic processes is better for facilitating supply chain operations. It is expected that the results may provide insight into the optimization of agro-product supply chain management in countries along the Belt and Road routes.

However, there are limitations to this study. For example, it concentrates on the effectiveness of emissions reduction without considering the marginal cost of such reduction. While focusing on the effects of incentivizing policies on the supply chain, it fails to consider other marketing measures. Future studies should determine the cost of carbon emission reduction in supply chains while coordinating and optimizing such emissions and incurred costs. They may even apply game theory to the interactive mechanism among stakeholders of an agro-product supply chain under different political contexts to facilitate policy implementation.

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Author Contributions: Rui Zhao was involved in conceptualizing the whole study, proposing the closed-loop model for agro-product supply chain, and writing the whole paper. Yiyun Liu and Zhenyan Zhang sketched the system dynamics casual loop diagram and stock flow diagram. Sidai Guo conducted the case study to collect the data. Ming-Lang Tseng improved the whole structure of the paper. Kuo-Jui Wu implemented the calculation to verify the proposed model.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

$$VFP = \text{IF THEN ELSE} (PIFS < 1000, FFI \times IPA, 0)$$

$$PIFS(n) = \text{INTEGRAL}(VFP(n) - VMA(n) - VARF(n), PIFS(0))$$

$$PIFS(0) = 1000$$

$$FFI = 1 \times FII$$

$$FII = VFI/DELAY1I(VFI, 1, 10 \text{ Million})$$

$$VFI \text{ (Variation of Farmers' Income)} = PP \text{ (Profit Per Product)} \times VMA \text{ (Variation of Marketing Acquisition)}$$

$$PP \text{ (Profit Per Product)} = AP \text{ (Acquisition Price)} - C \text{ (Cost)}$$

$$AP \text{ (Acquisition Price)} = \langle \text{Time} \rangle = [(0,0) - (10,10)], (1,5.5), (2,6), (3,7.5), (4,8), (5,9), (6,8.8), (7,10), (8,10), (9,10.2), (10,9))$$

$$PP \text{ (Profit Per Product)} = C \text{ (Cost)}$$

$$VMA = \text{IF THEN ELSE (PIFS} \leq 0, 0, \text{IF THEN ELSE (PIMS} > \text{INVENTORYCAPACITY, } 0, 1000 \times \text{FMR))}$$

$$FMR = MP - AP$$

$$FMR = FMR/DELAY1I(MR, 1, MR(0))$$

$$MR(0) = 1$$

$$PIMS(n) = \text{INTEGRAL}(VMA(N) - VCP(n) - VWRM(n), PIMS(0))$$

$$PIMS(0) = 1000$$

$$VCP = \text{IF THEN ELSE (PIMS} > 0, 1000/(FMP \times \text{FCD}), 0)$$

$$\text{FCD} = \text{PICS}/\text{DELAY1I}(\text{PICS}, 1, \text{VCP}(0))$$

$$\text{VCP}(0) = 0$$

$$\text{FMP} = \text{MP}/\text{DELAY1I}(\text{MP}, 1, \text{MP}(0))$$

$$\text{MP}(0) = 8$$

$$\text{MP (Marketing Price)} = \langle \text{Time} \rangle = [(0,0) - (10,10)], (1,8), (2,9.7), (3,10), (4,10.8), (5,11), (6,10.6), (7,11.8), (8,12), (9,13), (10,12.5))$$

$$\text{PICS}(n) = \text{INTEGRAL}(\text{VCFP}(N) - \text{VC}(n) - \text{VWGC}(n), \text{VCFP}(0))$$

$$\text{VCFP}(0) = 100$$

$$\text{VECRL} = (\text{PLRF} \times \text{PIFS} + \text{PLRM} \times \text{PIMS}) \times \text{FECT}$$

$$\text{ECRL}(n) = \text{INTEGRAL}(\text{VERAL}(n), 0)$$

In Scenario 1 of the redesigned supply chain,

$$AL = 0, \text{CELD} = 0.$$

In Scenario 2 of the redesigned supply chain,

$$AL(n) = \text{INTEGRAL}(\text{VWGC}(n), 0) \text{CELD}(n) = AL(n) \times \text{CEFL}$$

$$\text{VWGC (Variation of Waste Generation in Consuming Stage)} = \text{VCP (Variation of Consumers' purchasing)} \times \text{PLRC (Product Loss Rate of Consuming Stage)}$$

In Scenario 1 of the redesigned supply chain,

$$\text{VWRBP} = \text{VARF} + \text{VWRM},$$

$$\text{VARF} = \text{FIFS} \times \text{PLRF}, \text{VWRM} = \text{PLRM} \times \text{PLMS}, \text{VWGC} = \text{VCP} \times \text{PLR}.$$

In Scenario 2 of the redesigned supply chain,

$$\text{VWRBP} = \text{VARF} + \text{VWRM}, \text{ where } \text{VARF} = \text{FIFS} \times \text{PLRF}, \text{VWRM} = \text{PLRM} \times \text{PLMS}.$$

$$\text{VEC (Variation of Energy Consumption)} = \text{VECF} + \text{VECT} + \text{VECM} + \text{VECRL} - \text{VBP}$$

$$\text{TEC (Total Energy Consumption)} = \text{INTEGRAL}(\text{VEC}(n), \text{VEC}(0))$$

$$\text{VEC}(0) = 0$$

$$\text{VECF} = \text{PIFS} \times \text{FECFS}, \text{VECT} = \text{FECT} \times \text{VMA}, \text{VECM} = \text{PIMS} \times \text{FECMS}$$

$$\text{VCE (Variation of Carbon Emissions)} = \text{VCET (Variation of Carbon Emissions in Transportation)} + \text{VCEWT (Variation of Carbon Emissions in Waste Transportation)}$$

$$\text{TCE}(n) = \text{INTEGRAL}(\text{VCE}(n), \text{TCE}(n - 1))$$

$$\text{TCE}(0) = 1000$$

$$\text{VP (Variation of Total Products)} = \text{VFP (Variation of Farmers' Production)}$$

$$\text{TAP}(n) = \text{INTEGRAL}(\text{VP}(n), 0)$$

$$\text{CEP (Carbon Emissions Per Product)} = \text{TCE (Total Carbon Emissions)} / \text{TAP (Total Amount of Products)}$$

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