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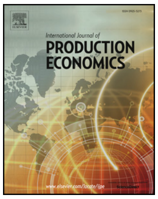

Simulation of land green supply chain based on system dynamics and policy optimization

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ABSTRACT

The dependence of human beings on natural resources is long-standing, and land resource is a crucial part of these natural resources. In recent years, land pollution and resource shortage have severely affected the normal lives of individuals. There is a growing appreciation of the need for studying the green supply chain of land. In this study, the land green supply chain is divided into subsystems of technology (T), energy (E), environment (E), and economy (E), which construct TEEE dynamic model. Based on the model, we simulate the develop trend of technology, energy, environment, and economy in Shandong Province from 2003 to 2020. Moreover, we find out optimal polices to realize economic and environmental objectives of 2020 of Shandong Province, and get the optimization scheme for environmental policy as below: water quota for farmland irrigation is 2780 m^2 per hectare, quota for urban water consumption is 33 m^3 per capita per year, quota for industrial water consumption is 8 m^3 per CNY10000 and unqualified rate of industrial waste water is 1%. If regulating and controlling as per such objectives, total industrial population will be reduced to 99.87 million, total industrial output value will reach CNY 44.68 trillion and environmental pollution degree will get down to 1.153.

1. Introduction

As an important step toward overall modernization of China, urbanization, together with industrialization, informalization, and agricultural modernization, has been considered as the carrier for building a comprehensively well-off society. The development of urbanization is inseparable from proper utilization of land resources. In recent years, with the development of China's economy and the increasing population, the frequency of land use and the scope of use have also increased. Since 2011, the urban population surpassed the rural population for the first time; by the end of 2014, the urban population was 749 million, which reached 54.77% of the total population of China, which also caused water shortages, air pollution, traffic congestion, and an insufficient ecological capacity. Currently, the most pressing issue for China is the wastage of resources that has resulted due to low land resource utilization efficiency, unbalanced regional development, and the low level of attraction of surplus rural labor force. Therefore, the need for the green supply chain of land is gaining attention.

With the acceleration of urbanization, land use has undergone tremendous changes. The real estate industry has developed rapidly. Land prices have continued to rise, and the growth rate of urban land use has surpassed the urban non-agricultural population growth rate. Reckless land disposal in development and construction and the serious problem of vacant expropriated land have left a large quantity of unused land. Land utilization in rural areas also has many problems that outstrip the national average. Meanwhile, land reform policies have also triggered serious problems such as low urban land utilization efficiency, accrual of land, and loss of agricultural acreage. If we take urbanization as an important symbol of economic development, then the emergence of these major urban diseases will not only make people's quality of life unimproved, but the development of the urban economy will also be limited by the environment and resources, and even need to be consumed. Partial economic growth needs to be achieved to maintain the current environment. Representatives at sessions of the National People's Congress and the Chinese Political Consultative Conference have pointed out that urban land utilization can be reduced to compel cities to maintain their population limit to alleviate urban stresses. These findings imply that China is experiencing backward economic development and wastage of resources.

The low efficiency of land resource utilization does not only exist in cities but also in rural areas. In most rural areas, to stimulate economic development, cultivated land is used to build schools and factories,

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thereby leading to a significant declining trend in the proportion of useful cultivated lands across the country. Agricultural acreage per capita reduced sharply from 1.58 mu (1 mu = 667 m^2) in 1996 to 0.34 mu in 2014, recording a significant decline. The 0.34 mu of privately-owned arable land has a low proportion of high-quality arable land and a poor resistance toward natural disasters. If calculated according to the current population growth rate, China's population will reach 1.45 billion by 2020, urbanization and industrialization will enter a period of rapid development, and the scale of urban land use will increase. There is a serious shortage of cultivated land resources in China, and a sizeable proportion of available land cannot be developed or utilized. Thus, the protection of productive cultivated land and seeking of adequate land for urban development have become the key factors of urbanization and industrialization in China. We believe that improvisation of supply efficiency of the green supply chain in the context of land and comprehensive development and utilization of land based on current land resources are crucial for solving urbanization problems.

By conducting a comprehensive survey of Chinese policy orientation, we find that the pace of development is closely related to land resources. In response to the land expropriation problem, China first proposed a corresponding land expropriation system at the 18th National Congress of the Communist Party of China, with the aim of improving the allocation ratio of land value-added revenue of farmers through land reforms. The Central Reform Leading Group explicitly stated at its fifth meeting that if we want to solve the problem of scarcity of land resources in China and advance and realize China's agricultural modernization, then we must deepen the land system reforms. In recent years, the Ministry of Land and Resources of China proposed a series of laws and regulations regarding land management. Resources and environment were the hot issues during the “two sessions” in 2015. Since environmental issues, such as land desertification, frequently occur, seriously affecting the sustainable development of the economy and society, it would be essential to prioritize solving the problem of land supply to accelerate the pace of urbanization.

Therefore, concerning the management of national land resources, we must find a way to strengthen environmental protection, emphasize clean resource exploitation and utilization, and optimize land use to improve the green supply ability of land resources. Additionally, China is already committed to establishing a “resource-saving and environmental-friendly” society and adhering to sustainable development strategies.

All these policies aimed at better management and utilization of land ensure that the pace of modernization and urbanization can be accelerated. Therefore, how can land resources be developed and used effectively without causing unnecessary damage? In this study, we attempt to simulate future trends emerging from the relationship between economy and land under different development schemes using a system modeling approach and find the optimal solution. Therefore, this simulation can be of great practical significance for proposing related policy recommendations.

Structure of this paper is as below: the second section is literature review; the third section provides the TEEE model of land green supply chain; the fourth section presents realization and optimization in view of SD of TEEE model; the fifth section gives conclusions and policy suggestions.

2. Literature review

The effective management and use of land resources is a crucial link in China's sustainable development strategy. This plays a pivotal role in the realization of economic development strategies. However, now, not everyone can realize the importance of land resource management (Meadows et al., 2014). If land deterioration is allowed to proceed unchecked, there may be severe consequences for the population (Haraldsson and Ólafsdòttir, 2006). Globally, countries are conducting research on the effective land utilization. For example, the Netherlands ensures that residents have enough living and development space by maintaining the balance among cities, water, and land, and plans to build 12 ecological corridors and ecological parks to protect the natural landscape (Zacharias et al., 2011). This provides a reference for the rational use of land resources. Canada emphasizes more on comprehensive management methods. McLain and Lee (1996) believed that traditional adaptive management methods do not achieve the desired results. To be effective, adaptive management methods should acquire knowledge from a variety of sources, use multiple methods, and develop new cooperation modes between stakeholders. Jhingran (1997) indicated that this model is conducive to the specialized management of individual resources, but the disadvantage was that various natural resources were linked loosely. However, for resources such as land and mineral resources, which are originally closely linked, if they are placed under multi-headed management, the comprehensive benefits of resources may not be fully realized. Bellamy and Johnson (2000) were also inclined toward comprehensive land resource utilization methods. Their research focused on the incorporation of the concept of sustainability into the agricultural management system of Australia. However, they also pointed out that this was challenging for both rural communities and government sectors. Lockwood et al. (2009) believed that the function of government departments should be to support the community and stakeholders. If trust mechanisms can be established in the management system, then it will make decentralized management more effective and more conducive to the establishment of cooperative natural resource management mechanisms. The study by Tennant and Lockie (2013) showed that lack of funds and unreasonable institutional structure are that the key factors affecting the development of integrated land protection networks. Relatively speaking, the United States is more inclined to adopt cooperative land resources management methods. Genskow (2009), by analyzing the cooperative natural resource management practices in Wisconsin, the USA, showed that the participation and response of government departments are conducive to the promotion of other stakeholders. Such participation will strengthen the use of additional resources.

Xu et al. (2011) observed that supply and demand in construction land use in China was imbalanced, which greatly restricted regional sustainable development. Han and He (2011) stressed that a circular economy must be achieved to realize sustainable development of agriculture in China. Martínez-Fernández et al. (2013) used the dynamic system model to analyze the agricultural prospects of the Mediterranean region and believed that the management of agricultural irrigation should be emphasized. However, with increased land utilization, the organic content of land continuously decreased, which may directly affect yield and the quality of crops (Yu et al., 2014). Research by Wang et al. (2016) showed that the organic content in the agricultural land in northern China is 10.8% lower than that in shrubland and 39.8% lower than that in forest land. Although China adopted a policy of returning the grain plots to forestry in 1999 to restore organic content and improve land supply and utilization efficiency, the expected effects were not achieved due to incomprehensive implementation of the policy (O'Connell et al., 2016). These studies show that the research on land supply capacity and utilization efficiency has penetrated various fields. With the gradual reduction of land resources, we must pay more attention to the protection of farmland in rural areas and maximize the potential of farmland production.

For so many land resource management models, which method is more reasonable? Which method is more suitable for the coordinated development of the local economy and the environment? There needs to be a reasonable evaluation method, and many scholars have already carried out relevant researches in this direction. Liu and Borthwick (2011) proposed the use of the bearing capacity to provide a new integrated measurement system for land environmental carrying capacity (CCE), including natural resource models, environmental assimilation models, ecosystem service capabilities, and social support capabilities. The basic index status of Ningbo and the status of the composite index

CCE were evaluated, respectively, and the focus on environmental pressure indicators in Ningbo was increased. Hua et al. (2011) adopted a pressure-state-response (PSR) model to evaluate land safety in the Dali Bai autonomous prefecture. Several scholars have also made different attempts to evaluate energy indicators. Vera and Abdalla (2006) selected Johannesburg, a developing country representative, to perform systematic energy index evaluations. Meyar-Naimi and Vaez-Zadeh (2012) further explored the energy index evaluation system based on 40 cases during 1994 and 2011. The geographic information technology (GIS) has been widely used in environmental science. For example, many scholars have used the GIS technology for researching the resource carrying capacity. Giuppponi and Vladimirova (2006) comprehensively evaluated the factors responsible for agricultural pressure on water resources within Europe by adopting a GIS-based Ag-PIE screening model. Lane (2010) mainly explored approaches that can effectively evaluate the carrying capacity of regional sustainable land utilization plans and found that no individual approach model can solve all carrying capacity problems. This was contrary to the findings of many scholars who worked out approaches that could solve population carrying capacity problems. Unfortunately, a specific practical model was not proposed by Lane. Graymore et al. (2010) proposed a new tool that can effectively evaluate regional sustainable development, sustaining human carrying capacity (SHCC), and empirically proved that the tool has the ability to monitor ecological system pressure in a region over a long period effectively.

From the above literature review, we can see that there have been many achievements in this field; however, most of them are limited by the lack of specialization of research subjects and weak applicability of research methods. Simply relying on a natural resource management research method is insufficient to obtain satisfactory results. As these highly specialized environmental performance evaluation technologies lack enough universality, it is hard to judge which analysis option is more appropriate in practical application courses. Even if some literature constructed and used similar evaluation approaches to analyze comparable real-life issues, their theoretical cores may significantly differ. In other words, any existing management approach with certain universal significance may, in practice, have its application range and limitations.

Nowadays, research of Supply Chain Management (SCM) is more and more inclined to integral perspective of which core lies in coordination and optimization among logistics, information stream and capital flow in supply chain. System Dynamic Method (SD) can better describe the material flow and information stream in SCM and simulate the whole supply chain as well to optimize it to find optimal policy measures through modification of model based on information feedback. Forrester (1958) who put forward the “Simple production- distribution model”, that is, the “Forrester model”, carried out the earliest application of SD into SCM research. This model expressed the condition of flowing of logistics in the whole supply chain and preliminarily revealed the Bullwhip effect of relationship between inventory and sale fluctuations in SCM with consideration of influences of information stream and time delay on logistics. Afterwards, Sterman (1989) designed the classical “Beer Game” and built a four-level model of supply chain system. Influences of demands change on inventory fluctuation were researched based on deep analysis of beer distribution game. Based on Sterman's model, many scholars modified the model as per practical problems and used SD to research a series of problems in SCM. Disney and Towill (2003) analyzed comprehensively the Bullwhip effect in the Vendor Managed Inventory (VMI) problem by using the SD method and put forward that VMI can better suppress the Bullwhip effect. Chang et al. (2006), by using the SD model, introduced fuzzy theory to make parameters fuzzified to meet with practical production process. Li et al. (2016), based on SD and time-related systematic activity under different operating conditions, put forward new modeling and simulation method to solve the dynamic risk management problem in the chemical supply chain transportation (CSCT).

In recent years, with environmental pollution getting increasingly serious, green supply chain has been gradually listed on the research agenda. Yu (2011) firstly put forward the concepts of green material rate, green productivity and green circulation rate and used SD to simulate key parts in green supply chain management. Simulation results showed that green circulation rate in green supply chain management has important functions on material rate and green productivity. Tian et al. (2014), based on game theory, constructed a model of SD to research the diffusion problem in green supply chain management in Chinese enterprises. Research results showed that subsidy policy was favorable to the diffusion of green supply chain management among enterprises. Yang (2015), by using the SD rate fundamental in-tree modeling, set up the feedback structure model for enterprises implementing green supply chain management to find leading factors of the system and put forward measures that favorable to the implementation of green supply chain management through analysis. Yan et al. (2016) carried out simulation analysis by using SD and statistical test to empirical data. Green supply chain management of high-tech enterprises was researched. Results showed that number of procured parts was closely related to cost efficiency and transportation time of each enterprise in supply chain. Cooperation between green suppliers in the supply chain was significantly positive on reducing cost mutually. Though SD has been widely used in SCM problems, there is rare literature that researched green supply chain management by using the SD method and only Bai et al. (2012) touched upon agricultural land use problem when researching green supply chain management. Based on SD model, this paper researched the green supply chain management system to seek for optimal policy measures to realize minimum negative output on environment while optimal resource allocation in the whole supply chain. We consider that economy, land, science, and environment cannot be separated and must be taken as an organic system. The proper utilization of land can be truly realized only by mastering the operational rules of factors in this system. Green supply chain of land is an important guarantee for coordinated development between environment and economy. However, several non-linear problems cannot be quantified often due to the complexity of system research. That is why this paper takes the green supply chain of land as its research object.

3. Construction of TEEE model of land green supply chain

Optimization of land green supply chain needs to consider proper allocation of land resource, sustainable development of land environment, optimization of land economic structure, coordination between technology and resource, economy and environment. Based on such thought, we referenced the thought of Rafael (2013) to divide land supply chain into four subsystems, that is, technology (T), economy (E), energy (E) and environment (E). Each subsystem includes input, production sector and output. Energy output of energy subsystem will be taken as energy input of other three subsystems. Energy is combined with labor force and capital in economy subsystem for production. Desirable output realizes internal circulation in subsystem through consumption on the one hand, and on the other hand, enters the technology subsystem to support technological research and development. A part of undesirable output circulates within the subsystem while the rest part flows into the environment subsystem. Energy is combined with scientists and R&D in technology subsystem for scientific innovation to output four kinds of technology: one is the exploiting technology that stimulate effective exploitation and utilization of energies in energy subsystem; one is the productive technology that stimulate efficiency of production in economy subsystem; one is the energy-saving technology that reduce energy consumption and the fourth is the emission reduction technology that lowering pollution discharge. Pollution discharge in technology subsystem directly enters into the environment subsystem. Environment subsystem produces by using its own repairing capacity and input of such production is pollutant while

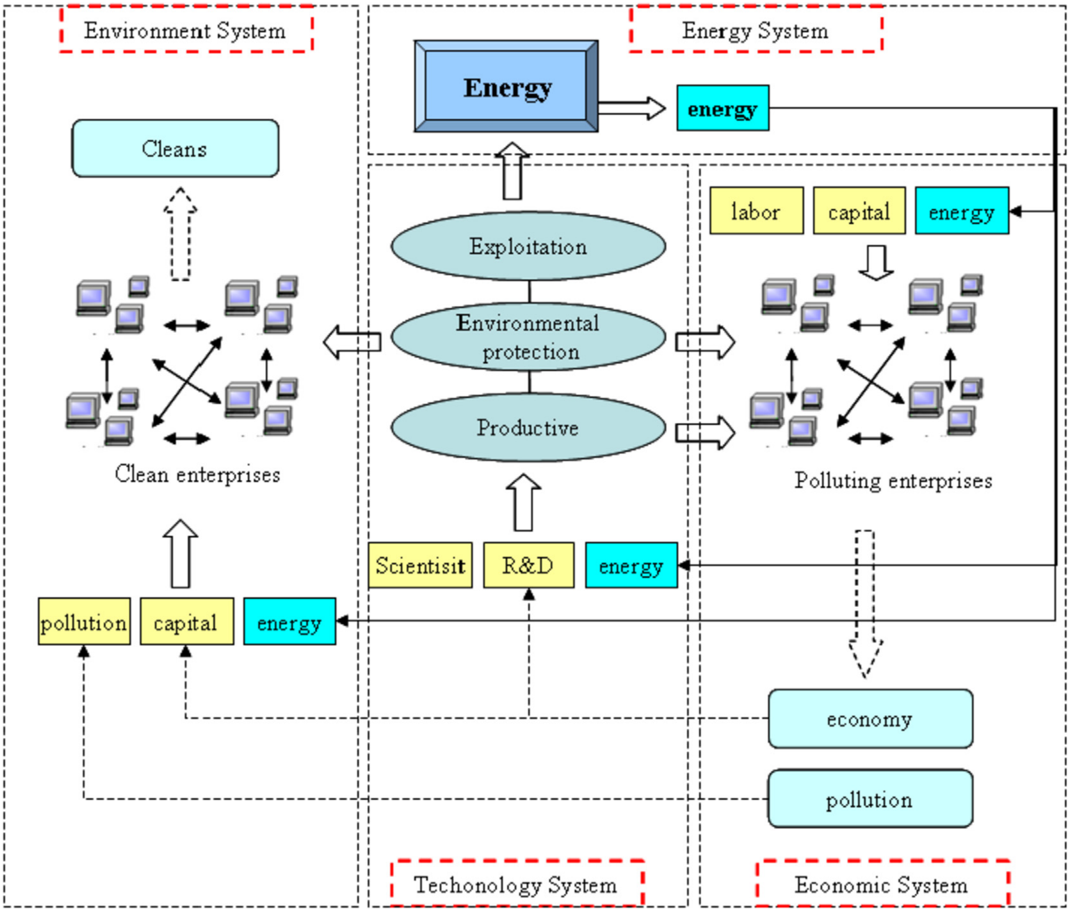

Fig. 1. Explanatory Chart of TEEE model.

output is clean product after pollutant being cleaned. These four subsystems are mutually connected and interactive that form a big system of technology, economy, energy and environment. We call it the TEEE system as showed in Fig. 1. And in order to facilitate the causal and flow graphs, we abbreviate the many variables involved in this paper, as shown in Table 1 below:

As system that composed of TEEE model involves many variables that cannot be analyzed by one single equation, we tried to use the SD method to research it. Compared with operational approach model and econometric model, System Dynamics (SD) can comprehensively reflect various kinds of influence factors in and out of the system and the integral dynamic activity of the system. Besides, we can continuously adjust the SD model according to changes of real systems to make our observed variables satisfactory. We firstly fit causal graphs to each subsystem respectively and simulate the state of each subsystem. If simulation and real values of subsystems pass the credibility test, we then connect each subsystem together to construct the TEEE SD flow chart.

Reliability test of model is to test the rationality of variables by using actual data to check the degree of accordance of established model with practical experience. The simple and effective way is to carry out relative error test to actual data and results of model. General expression of relative error is:

$$\varepsilon_{it} = \left| \frac{y_{it}^1 - y_{it}}{y_{it}} \right| \tag{1}$$

In the equation, y_{it}^1 and y_{it} respectively refers to actual value and simulated value of the ith variable in the tth year; ε_{it} refers to relative error of the ith variable in the tth year. It is considered that general simulation effect of the model is good if 70% or more variables have relative errors that smaller than 0.05 and relative error of all variables equal to or smaller than 10%.

3.1. Energy subsystem

Grain is not only an important component of energy subsystem but also the most fundamental expression of man-earth relationship. It includes two parts, grain production and grain utilization. In energy subsystem, we take grain per-unit-area yield as core variable and grain total yield is decided by both grain per-unit-area yield and sowing area of grain crop. Total population and grain consumption level per capita decide the total grain demand; total yield and demand of final grain together decide the supply and demand ratio of grain. Fig. 2 is a causal graph that only qualitatively expresses relationships among variables and reflects influences of positive and negative feedback. Only after establishing causal graphs of every subsystem can numerical relationship among variables be effectively and quantitatively analyzed.

3.2. Economy subsystem

In economy subsystem, total industrial output value and effective irrigation area of farmland are taken as core variables. Judging from industrial level, the higher the total industrial output value, the better the economic development and the more the industrial water consumption. Similarly, effective irrigation area of farmland decides the agricultural water consumption. Changes of industrial water consumption and agricultural water consumption will make the total water demand change and finally affect the supply and demand ratio of water resource. Causal relationship is showed in Fig. 3.

Table 1
Index descriptions.

Abbreviation	Indicator	Abbreviation	Indicator
TP	Total population	CPCWS	Comprehensive production capacity of water supply
GPY	Grain per-unit-area yield	GOVP	Grain occupancy volume per capita
TIOV	Total industrial output value	GSDR	Grain supply-demand ratio
EFIA	Effective farmland irrigation area	ITIOV	Increment of total industrial output value
GCABA	Green coverage area in built up area	AGRTIOV	Annual growth rate of total industrial output value
COD	COD stock	QQIWW	Qualified quantity of industrial waste water
SD	Sulfur dioxide stock	IWC	Industrial water consumption
SW	Solid waste stock	QIWC	Quota for industrial water consumption
PDR	Population death rate	WD	Water demand
CI	Cropping index	AWC	Agricultural water consumption
GCLP	Grain consumption level per capita	EWC	Ecological water consumption
DWQRR	Domestic water quota for rural residents	DWC	Domestic Water consumption
DWQUR	Domestic water quota for urban residents	WSDR	Water supply-demand ratio
WQFI	Water quota for farmland net irrigation	WS	Water supply
QRIWW	Qualified rate of industrial waste water	IPIOV	Increment of primary industrial output value
IGPY	Increment of grain per-unit-area yield	VEFIA	Variation of Effective farmland irrigation area
TGY	Total grain yield	CREIA	Change rate of effective irrigation area
SAGC	Sown area of grain crops	NBP	Newly-born population
FA	Farmland area	RNBP	Rate of newly-born population
IRGPY	Increment rate of grain per-unit-area yield	DP	Dead population
TGD	Total grain demand	ISIOV	Increment of secondary industrial output value
UP	Urban population	RDWC	Rural domestic water consumption
RU	Rate of urbanization	UDWC	Urban domestic water consumption
RP	Rural population	EPD	Environmental pollution degree
ECOD	Emitted COD	RPDP	Relative pollution degree of pollutant
CODTR	COD treatment rate	VGCABA	Variation of green coverage area in built up area
TCOD	Treated COD	VRGCABA	Variation rate of Green coverage area in built up area
DSW	Discharged solid waste	WQLG	Water quota for landscaping of Green
SWTR	Solid waste treatment rate	ESD	Emitted sulfur dioxide
TSW	Treated solid waste	SDTR	Sulfur dioxide treatment rate
ILAR	Industrial land area ratio	TSD	Treated sulfur dioxide
FAR	Farmland area ratio	TPD	Total pollutant discharge
UCLA	Urban construction land area	RLAR	Residential land area ratio

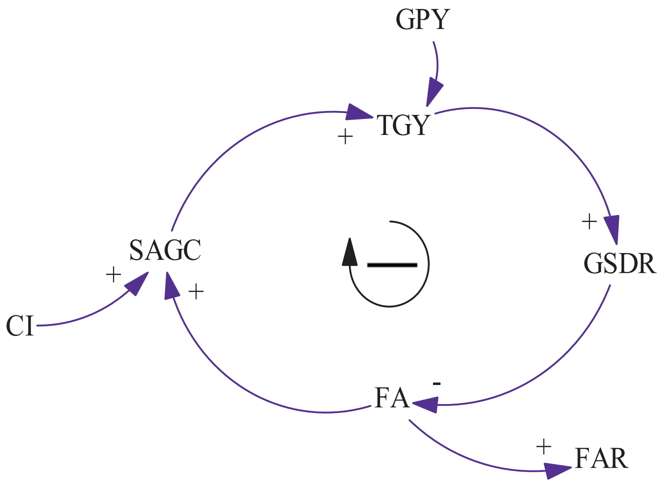

Fig. 2. Causal graph of energy subsystem.

3.3. Technology subsystem

In agricultural production and utilization, technological progress is mainly reflected in the improvement of efficiency of labor force to land use. Therefore, to land green supply chain, population will directly influence the degree of technological content of land. This shows that we can take population as the substitute index for technological factor and combine it with other subsystems. Here we take total population as a core variable and divide it into urban population and rural population. Suppose that urban and rural household domestic water consumption is a fixed value, number of both urban and rural population will decide the total domestic water consumption together and further influence the water demand and water supply-demand ratio in the whole system. Meantime, suppose grain consumption level per capita is a fixed value, increase of total population will increase the demand for grain and further influence the grain supply-demand ratio. Causal graph

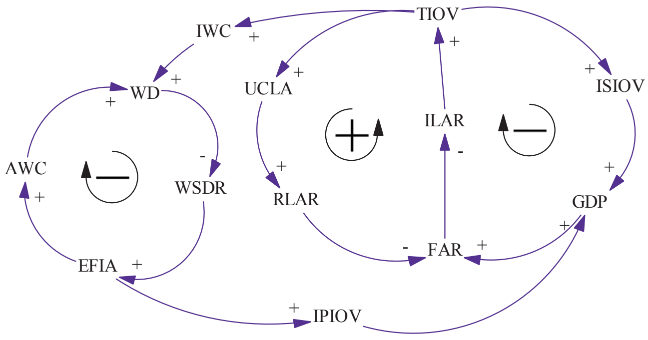

Fig. 3. Causal relationship of economy subsystem.

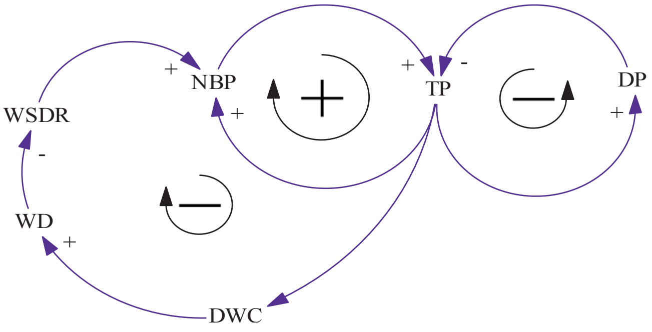

Fig. 4. Causal graph for population subsystem.

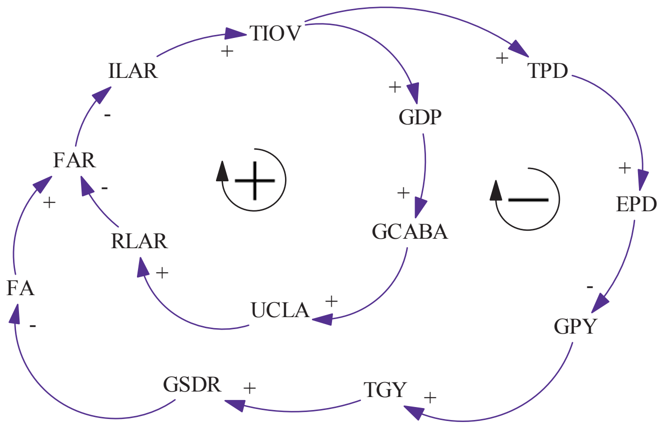

Fig. 5. Causal graph for environment subsystem.

for population subsystem is showed in Fig. 4. Similarly, all variable indexes will be reflected in the TEEE SD flow graph (see Fig. 5).

3.4. Environment subsystem

In this paper, water pollution, air pollution and solid waste pollution in the environment subsystem are analyzed with emphasis. COD stock that represents water pollution degree, sulfur dioxide stock that represents air pollution degree and solid waste stock that represents solid waste pollution are selected as core variables. Degree of environmental pollution in the whole environment subsystem is analyzed with consideration of influence of total industrial output value on emission of all above pollutants. In aspect of ecological environment, green coverage area in built up area is taken as a core variable. Water quota for landscaping will change as time passes by and ecological water demand, total water demand and water supply-demand ratio are decided by green coverage area and water quota for landscaping together.

4. SD realization and optimization of TEEE model

Causal graph can qualitatively describe feedback structure, but cannot quantitatively describe numerical relationship among each variable and time-dependent change rules of variables. Hence, during modeling, components of each subsystem should be connected as per their internal correlations on the basis of interior causal relationship analysis of the subsystem. Therefore, we introduced state variable, speed variable and auxiliary variable to set up the flow graph of system structure that is able to describe functional relationship among each variable.

In this paper, administrative boundary of Shandong Province is taken as spatial research boundary and research time is from 2003 to 2020. Data from 2003 to 2012 are actual historical data and data from 2013 to 2020 are predicted by the model. Time step is one year. 8 state variables including total population, total industrial output value, effective irrigation area of farmland, green coverage area of built up area, grain per-unit-area yield, COD stock, sulfur dioxide stock and solid waste stock, 12 speed variables, 37 auxiliary variables and 10 constant variables are set up. Based on causal graph of each subsystem, the integrated SD flow graph of land green supply chain is constructed (Fig. 6) (see Table 2).

Initial values of state variables are acquired through calculation as per Statistical Yearbook of Shandong Province over the years. Data are showed in Table 1. Constant variables are system internal variables that directly function on state variables. 15 constant variables are involved in this paper. For constant variables that changed not much over the years such as death rate and cropping index, mean values are taken to decide the values of constant variables. Grain consumption level per capita is the product of urban and rural population ratio, urban and rural grain purchase per capita and outward consumption ratio. Urban household domestic water quota is acquired as per Domestic Water Consumption Standard in Shandong Province and rural household domestic water quota is acquired through calculation based on urban household domestic water quota. Data of net farmland irrigation water quota come from the Irrigation Quota for Main Crops in Shandong Province. Values of other constant parameters are acquired through calculation as per Statistical Yearbook of Shandong Province and data from the Bureau of Land and Resources. Please refer to Table 3 for details.

First, we list relational expressions in the four subsystems of energy, economy, technology, and environment, according to the causal graph in the following analysis. Then, we establish the relevant subsystem flow graphs for each of the abovementioned subsystems and combine these flow graphs with the TEEE total system flow graph as shown in Fig. 6. Finally, we operate the complete land green supply chain dynamic model TEEE. We conduct reliability tests (relative error test) of the evaluation results of each subsystem, and present our analysis.

Relational expressions of energy subsystem are:

Grain per-unit-area yield = ∫ Increment of grain per-unit-area yield (2)

Total grain yield = Grain per-unit-area yield × Sown area of grain crops (3)

Sown area of grain crops = Cropping index × Farmland area (4)

Increment of grain per-unit-area yield = Grain per-unit-area yield × Increment rate of grain per-unit-area yield (5)

Total grain demand = Grain consumption level per capita × Total population (6)

Grain occupancy volume per capita = Total grain yield / Total population (7)

Grain supply-demand ratio = Total grain yield / Total grain demand (8)

Relational expressions of economic subsystem are:

Formulae (9) to (17) are relevant formulae of total industrial output value and effective farmland irrigation area.

Total industrial output value = ∫ Increment of total industrial output value (9)

Annual increment of total industrial output value = Total industrial output value × Annual growth rate of total industrial output value (10)

Qualified quantity of industrial waste water = Industrial water consumption × Qualified rate of industrial waste water (11)

Industrial water consumption = Total industrial output value × Quota for industrial water consumption (12)

Water demand = Agricultural water consumption + Industrial water consumption + Ecological water consumption + Domestic Water consumption (13)

Water supply-demand ratio = Water supply/Water demand (14)

Agricultural water consumption = Effective farmland irrigation area × Water quota for net farmland irrigation (15)

Effective farmland irrigation area = ∫ Variation of Effective farmland irrigation area (16)

Variation of Effective farmland irrigation area = Effective farmland irrigation area × Change rate of effective irrigation area (17)

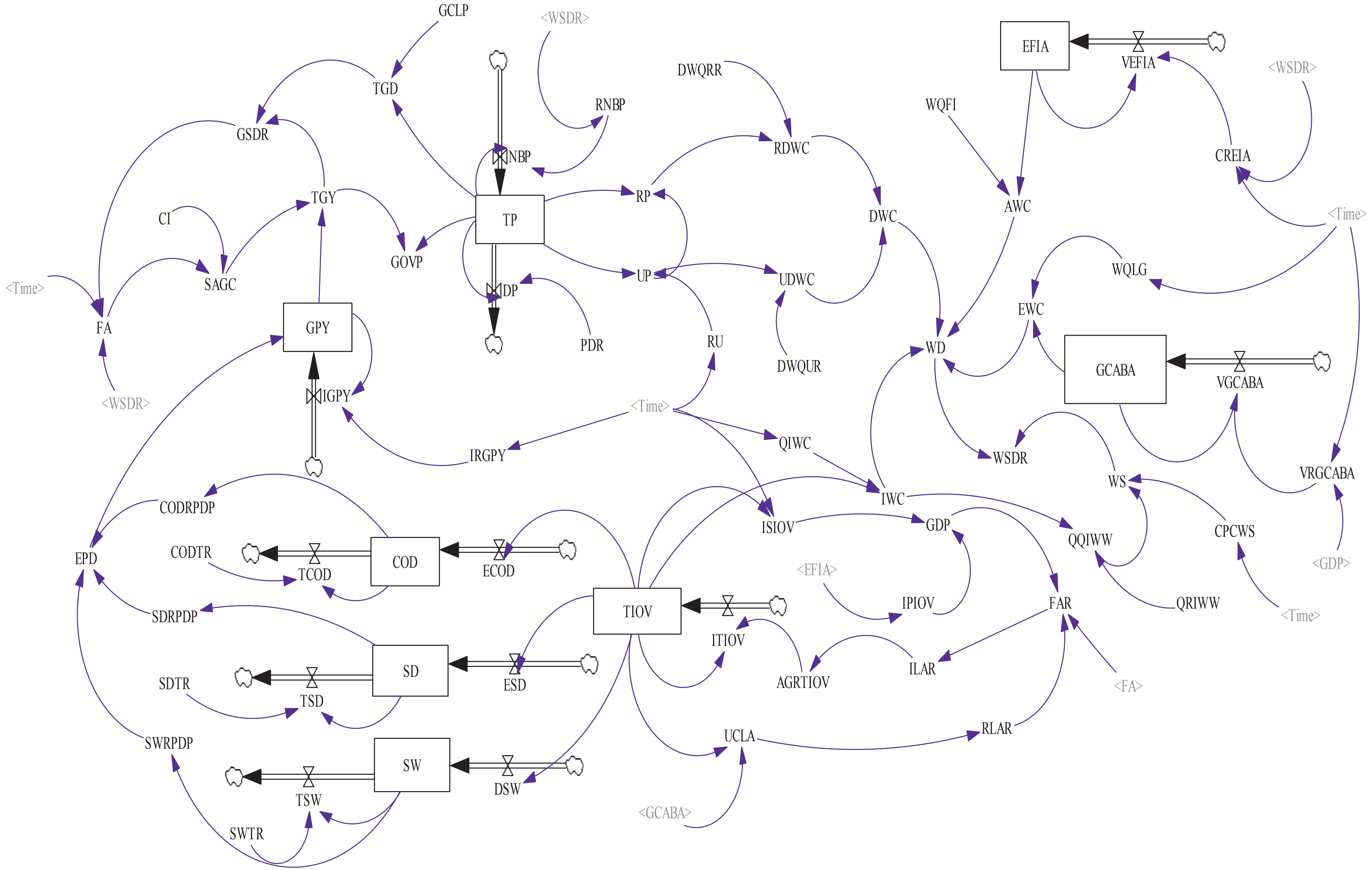

Fig. 6. TEEE SD flow graph.

Table 2
Initial values of state variables.

State variables	Initial value	Unit
Total population	9125	10000 persons
Grain per-unit-area yield	5355	kg/hectare
Total industrial output value	19891.54	CNY100 million
Effective farmland irrigation area	476.079	10000 ha
Green coverage area in built up area	77837	Hectare
COD stock	40.63	10000 tons
Sulfur dioxide stock	184	10000 tons
Solid waste stock	6786	10000 tons

Data source: Statistical Yearbook of Shandong Province from 2003 to 2012.

Table 3
Table of constant parameters.

Constant parameters	Value	Unit
Population death rate	0.0634	%
Cropping index	1.5	Time
Grain consumption level per capita	386.6	Kg/person/year
Domestic water quota for rural residents	21.9	m^2/person/year
Domestic water quota for urban residents	36.5	m^2/person/year
Water quota for farmland net irrigation	3103.67	m^2/hectare
Qualified rate of industrial waste water	98	%

Note: Data come from Statistical Yearbook of Shandong Province from 2003 to 2012. Scatter diagram about relationships among variables are drawn to judge whether relationships are linear or not. For variables with linear relationship, linear regression is taken to find the variable relationship formula; for variables with nonlinear relationship, formulae are decided by table function that built in Vensim software.

Relational expressions of technology subsystem are:

Newly-born population = Total population × Rate of newly-born population (18)

Dead population = Total population × Rate of dead population (19)

Total population = ∫ (Newly-born population- Dead population) (20)

Urban population = Total population × Rate of urbanization (21)

Rural population = Total population - Urban population (22)

Rural domestic water consumption = Rural population × Domestic water quota for rural residents (23)

Urban domestic water consumption = Urban population + Domestic water quota for urban residents (24)

Domestic water consumption = Rural domestic water consumption + Urban domestic water consumption (25)

Relational expressions of environment subsystem are:

COD stock = ∫ (Emitted COD-Treated COD) (26)

Sulfur dioxide stock = ∫ (Emitted sulfur dioxide - Treated sulfur dioxide) (27)

Solid waste stock = ∫ (Discharged solid waste - Treated solid waste) (28)

Treated COD = COD stock × COD treatment rate (29)

Treated sulfur dioxide = Sulfur dioxide stock × Sulfur dioxide treatment rate (30)

Treated solid waste = Solid waste stock × Solid waste treatment rate (31)

Environmental pollution degree = ΣRelative pollution degree of pollutant × Constant (32)

Table 4
Relative error of energy subsystem.

Year	Grain per-unit-area yield (kg/hectare)	Simulated value	Relative error	Farmland area 1000 ha	Simulated value	Relative error
2003	5355	5355	0.0000	7070	7070	0.0000
2004	5570	5570	0.0000	6951	6950	0.0001
2005	5837	5837	0.0000	6908	6907	0.0001
2006	5848	5848	0.0000	6882	6881	0.0001
2007	5981	5981	0.0000	6855	6855	0.0000
2008	6125	6124	0.0002	7511	7510	0.0001
2009	6140	6140	0.0000	7150	7149	0.0001
2010	6120	6120	0.0000	7176	7175	0.0001
2011	6194	6193	0.0002	7207	7207	0.0000
2012	6264	6263	0.0002	7636	7635	0.0001

Green coverage area in built up area = ∫ Variation of green coverage area in built up area (33)

Variation of green coverage area in built up area = Green area in built up area × Variation rate of Green coverage area in built up area (34)

Ecological water consumption = Water quota for landscapping of Green × Green coverage area in built up area (35)

Here, we analyze the evaluation results of the energy subsystem and also conduct a reliability test (relative error test). In the modeling in the previous text, it is pointed out that grain is not only an important part of the energy subsystem, but is also the most fundamental expression of the “man-earth” relationship. Therefore, in the energy subsystem, we take grain single yield as a core variable. True values, simulated values, and relative errors of grain single yield and agricultural acreage, and the representatives of other variables are shown in Table 4 as below (the results of reliability tests of other relevant variables are consistent, but they are not presented in this paper due to the length requirement). From the results in Table 4 we can see that during the periods between 2003 and 2012, relative error between true data and model results in this paper was far less than 0.05. Therefore, the simulation effect of the TEEE model of the energy subsystem is good enough to depict practical situations concerning the energy subsystem in reality.

Second, we analyze the evaluation results of the economy subsystem and conduct a reliability test (relative error test). In the modeling in the previous text, total industrial output value and effective irrigation area of farmland are taken as core variables in this paper. True values, simulated values, and relative errors of the abovementioned two variables are presented in Table 5, from which we can see that similar to the energy subsystem, during the period between 2003 and 2012, the relative error between true data and model results in this paper was far less than 0.05. Therefore, the simulation effect of the TEEE model of the economy subsystem is good enough to depict practical situations concerning the economy subsystem in reality.

Third, we analyze the evaluation results of the technology subsystem and conduct a reliability test (relative error test). In the modeling in the previous text, the size of population will directly affect the technological content of land with respect to the land green supply chain. Therefore, we take population as the proxy variable of the technological factor and combine it with other subsystems as the core variable of the technology subsystem. From Table 6, we can see that during the period between 2003 and 2012, relative error between true data and model results in this paper was still far less than 0.05 even though there was a slight increase. Thus, the simulation effect of the TEEE model of the technology subsystem is good enough to depict practical situations concerning the technology subsystem in reality.

Finally, we analyze the evaluation results of the environment

Table 5
Relative error of economy subsystem.

Year	Total industrial output value (CNY 100 million)	Simulated value	Relative error	Effective farmland irrigation area (1000 ha)	Simulated value	Relative error
2003	19,892	19,891	0.0000	4761	4760	0.0002
2004	26,295	26,189	0.0040	4767	4766	0.0002
2005	35,387	35,082	0.0086	4790	4789	0.0002
2006	43,900	44,898	−0.0227	4818	4818	0.0000
2007	54,428	55,678	−0.0230	4837	4836	0.0002
2008	62,959	66,300	−0.0531	4867	4866	0.0001
2009	71,209	77,410	−0.0871	4897	4896	0.0002
2010	83,851	89,075	−0.0623	4955	4955	0.0001
2011	99,505	105,400	−0.0592	4987	4986	0.0002
2012	114,707	121,500	−0.0592	5018	5018	0.0001

Table 6
Relative error of technology subsystem.

Year	Total population 10000 persons	Simulated value	Relative error	Urban population 10000 persons	Simulated value	Relative error
2003	9125	9125	0.0000	2833	2833	0.0000
2004	9180	9172	0.0009	2951	2948	0.0010
2005	9248	9220	0.0030	3147	3137	0.0032
2006	9309	9268	0.0044	3228	3214	0.0043
2007	9367	9317	0.0053	3436	3417	0.0055
2008	9417	9366	0.0054	3532	3512	0.0057
2009	9470	9415	0.0058	3548	3527	0.0059
2010	9579	9464	0.0120	3839	3793	0.0120
2011	9637	9513	0.0129	3945	3894	0.0129
2012	9685	9563	0.0126	4021	3970	0.0127

Table 7
Relative error of environment subsystem.

Year	Green area (hectare)	Simulated value	Relative error	Emitted sulfur dioxide (1000 tons)	Simulated value	Relative error
2003	77,837	77,837	0.0000	1840	1840	0.0000
2004	87,684	87,684	0.0000	1820	1820	0.0000
2005	98,926	98,925	0.0000	2000	1993	0.0035
2006	108,411	108410	0.0000	1960	1946	0.0071
2007	118,973	118,972	0.0000	1822	1802	0.0110
2008	129,788	129,787	0.0000	1692	1650	0.0248
2009	138,923	138,922	0.0000	1590	1564	0.0164
2010	147,904	147,903	0.0000	1538	1634	−0.0626
2011	155,699	155,698	0.0000	1827	1796	0.0172
2012	165,409	165,408	0.0000	1749	1748	0.0005

subsystem and conduct a reliability test (relative error test). In the modeling in the previous text, this paper focuses on water pollution, atmospheric pollution, and solid wastes pollution. COD stock, sulfur dioxide emission, and solid wastes stock are taken as core variables of water pollution, atmospheric pollution, and solid wastes pollution, respectively. True values, simulated values, and relative errors of sulfur dioxide emission (the core variable) and green area (representative of other variables) are presented in Table 7 as shown below (reliability test results of other core variables and relevant variables are consistent, but they are not presented in this paper due to the length requirement). From Table 7, we can see that similar to the abovementioned subsystems, during the period between 2003 and 2012, relative error between true data and model results in this paper was far less than 0.05. Therefore, the simulation effect of the TEEE model of the environment subsystem is also good enough to depict practical situations concerning the environment subsystem in reality.

To sum up, we run the complete land green supply chain dynamic model TEEE and analyze our evaluation results and conduct reliability tests (relative error test) for each subsystem. Judging from the results of our analysis, the simulation effect of the model established in this paper is good enough to depict practical conditions for every subsystem in reality. Therefore, the establishment of this model is not only helpful in predicting changes in every variable in the future, but is also favorable for carrying out an efficiency evaluation of the input and output of land green supply chain further, to find the best economy-environment policy measures.

In addition, we applied system dynamics to predict and simulate the land supply chain. And through this procedure, we can understand what decisions can be made and what kind of policy results can be produced more clearly. By planning data envelopment analysis, policymakers can better understand how to improve land utilization efficiency to solve the land shortage issue.

In the 11th Five-year plan, China put forward to reduce energy consumption per GDP in 2010 by 20% as compared with that in 2005; in the 12th Five-year plan, it is stipulated to reduce carbon emission in 2020 by 40%–45% as compared with that in 2005. However, we still have questions on policy enactment: which policy is the optimal? Which is the best way to reach our policy objectives? With these questions, this paper made predictions to every index in 2020.

In the third section, we simulated the complex system through TEEE model and acquired relatively stable results. In the fourth section, we will take TEEE system as a "camera obscura" without considering internal relationships among variables and evaluate the total "energy" input and total "energy" output in this system from macroscopic perspective. In TEEE model, "energy" input can be taken as policy index. By simulating policy enactment and through "camera obscura" treatment of the index can "energy" output such as energy saving, emission reduction and economic growth can be realized. Hence, the higher the fitting precision of data, the more accurate the predicted "energy" output. Therefore, input indexes can be policy-controllable quota for industrial water consumption, quota for domestic water consumption of urban residents, quota for farmland net irrigation water and unqualified rate of industrial waste water; output indexes can be total population, total industrial output value and environmental pollution degree.

We try to measure the optimal policy standard by using the BCC model with variable returns to scale. Formula is as below:

$$\min\ Z^0$$
$$\begin{cases} \sum_{j=1}^{n} X_j^0 \lambda_j \le Z^0 X_0^0 \\ \sum_{j=1}^{n} Y_j^0 \lambda_j \ge Y_0^0 \\ \sum_{j=1}^{n} \lambda_j < 1 \\ \lambda_j \ge 0, j = 1,2, \cdots n \end{cases} \tag{36}$$

Change the fourth input index while maintaining other three input indexes unchanged. Try every possible input value in the mode of arithmetic progression construction as adjustable policy scheme. For every input index, total population, total industrial output value and environmental pollution degree in 2020 are all simulated through TEEE system. In this way can we get the total input and output of the system.

Then, we carry out efficiency evaluation to the acquired input and output in which way to know the more effective policy schemes. If government carries out macro-control by following the most effective mode, then the efficiency of the whole system can be the optimal.

Though DEA model requires input as little as possible while output as much as possible, in practical production, unlimited reduction of input is not allowed. During efficiency evaluation we find that there will always be a nodal point during progressive increase of input in each group. Before such nodal point, improvement of efficiency value is not significant while after such point efficiency value will be improved greatly. Thus, we use the scheme that corresponding to this nodal point as the optimal policy scheme. According to this thought, we get the optimization scheme for environmental policy as below: water quota for farmland irrigation is 2780 m^2 per hectare, quota for urban water consumption is 33 m^3 per capita per year, quota for industrial water consumption is 8 m^3 per CNY10000 and unqualified rate of industrial waste water is 1%. If regulating and controlling as per such objectives, total industrial population will be reduced to 99.87 million, total industrial output value will reach CNY 44.68 trillion and environmental pollution degree will be 1.153.

5. Conclusions and policy suggestions

Through the SD model analysis, it is possible to completely simulate nonlinear and systematic complex problems and integrate the four modules of economy, land, technology, and environment. The relationships between variables completely follow the results of the system and were not set to a specific function relationship in advance. This significantly contributed toward enhancing the predictability of the model.

In addition, we applied system dynamics to predict and simulate the land supply chain, and we clearly understood what decisions can be made and what kind of policy results can be produced. By planning data envelopment analysis, policymakers can better understand how to improve land utilization efficiency to solve the land shortage issue.

Compared with research of traditional supply chain, emphasis of this paper lies in "green", that is, influence of each link during land use on environment. By establishing TEEE model, all indexes that relevant to land use are included into technology, economy, energy and environment subsystems. SD model is used to combine these four subsystems and their indexes to simulate practical production processes and policies. For green supply chain of land, resource, environment, technology and economy are all sensitive restrictive factors. Through screening of different factors and combination of them, different schemes can be formed for analysis. To find the optimal policy measures, we used DEA model to analyze the efficiency of input and output of TEEE system. The higher the efficiency value, the better the effects of policy.

Land is a kind of scarce resource. Therefore, it is necessary to take measures to improve the output of land per unit area such as expand irrigation area, increase cropping index and improve chemical fertilizer use structure to increase per-unit-area yield of gain. Traditional resource use methods should be replaced with modern technologies to greatly improve the utilization ratio of resources. Besides, cultivated land protection should be enhanced; comprehensive production ability of land should be improved; land ecological environment should be adjusted as per local conditions; land use structure should be optimized and utilization ratio of construction land should be increased.

Economic growth has important effect on green supply chain of land. Moderate economic scale and structure are favorable to sustainable and intensive use of land. When pursuing for maximization of economic benefits, economic development mode should be changed and optimization of industrial structure should be quickened to ensure coordinated development among economy, resource, environment and technology to maximize the comprehensive benefits. As free trade can be carried out among different regions. One region can give full play its comparative advantages and develop industrials that fit for local lands resources while protect its land resources at the same time. Coastal land may change because of functions of seas and reclamation of land from sea. Therefore, research of land green supply chain should be a long-term dynamic process and we will consider this in further research as well to set up more impeccable green supply chain system of land.

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References

Bai, Y., Ouyang, Y.F., Pang, J.S., 2012. Biofuel supply chain design under competitive agricultural land use and feedstock market equilibrium. Energy Econ. 34, 1623–1633.

Bellamy, J.A., Johnson, A.K.L., 2000. Integrated resource management: moving from rhetoric to practice in Australian agriculture. Environ. Manag. 25 (3), 265–280.

Chang, P.T., Lin, K.P., Wu, M.S., 2006. Applying fuzzy arithmetic to system dynamics for the customer-producer-employment model. Int. J. Syst. Technol. 37, 673–698.

Disney, S.M., Towill, D.R., 2003. The effect of vendor managed inventory in dynamics on the Bullwhip effect in supply chains. Int. J. Prod. Econ. 85, 199–215.

Forrester, J.W., 1958. Industrial Dynamics: a major breakthrough for decision makers. Harv. Bus. Rev. 36 (4), 37–66.

Genskow, K.D., 2009. Catalyzing collaboration: Wisconsin's agency-initiated basin partnerships. Environ. Manag. 43 (3), 411–424.

Giuppponi, C., Vladimirova, I., 2006. Ag-PIE: a GIS-based screening model for assessing agricultural pressures and impacts on water quality on a European scale. Sci. Total Environ. 359 (1), 57–75.

Graymore, M., Sipe, N.G., Rickson, R.E., 2010. Sustaining human carrying capacity: a tool for regional sustainability assessment. Ecol. Econ. 69 (3), 459–468.

Han, Jun, He, Xiang, 2011. Development of circular economy is a fundamental way to achieve agriculture sustainable development in China. Energy Proced. 5, 1530–1534.

Haraldsson, V.H., Ólafsdòttir, R., 2006. A novel modeling approach for evaluating the preindustrial natural carrying capacity of human population in Iceland. Sci. Total Environ. 372 (1), 109–119.

Hua, Y.E., Yan, M.A., Linin, D., 2011. Land ecological security assessment for Bai autonomous prefecture of Dali based using PSR model—with data in 2009 as case. Energy Proced. 5, 2172–2177.

Jhingran, I.G., 1997. National mineral policy of India—an overview. Resour. Pol. 23 (1), 91–96.

Lane, M., 2010. The carrying capacity imperative: assessing regional carrying capacity methodologies for sustainable land-use planning. Land Use Pol. 27 (4), 1038–1045.

Li, C.Y., Ren, J., Wang, H.Y., 2016. A system dynamics simulation model of chemical supply chain transportation risk management systems. Comput. Chem. Eng. 89 (9), 71–83.

Liu, R.Z., Borthwick, A.G., 2011. Measurement and assessment of carrying capacity of the environment in Ningbo, China. J. Environ. Manag. 92 (8), 2047–2053.

Lockwood, M., Davidson, J., Curtis, A., et al., 2009. Multi-level environmental governance: lessons from Australian natural resource management. Aust. Geogr. 40 (2), 169–186.

Martínez-Fernández, J., Esteve-Selma, M.A., Baños-González, I., et al., 2013. Sustainability of Mediterranean irrigated agro-landscapes. Ecol. Model. 248, 11–19.

McLain, R.J., Lee, R.G., 1996. Adaptive management: promises and pitfalls. Environ. Manag. 20 (4), 437–448.

Meadows, J., Emtage, N., Herbohn, J., 2014. Engaging Australian small-scale lifestyle landowners in natural resource management programmes–Perceptions, past experiences and policy implications. Land Use Pol. 36, 618–627.

Meyar-Naimi, H., Vaez-Zadeh, S., 2012. Sustainable development based energy policy making frameworks, a critical review. Energy Policy 351–361.

O'Connell, J.L., Daniel, D.W., McMurry, S.T., Smith, L.M., 2016. Soil organic carbon in playas and adjacent prairies cropland, and Conservation Reserve Program land of the High Plains. USA. Soil Tillage Res. 156, 16–24.

Sterman, J.D., 1989. Modeling managerial behavior: misperception of feedback in a dynamic making experiment. Manag. Technol. 35 (3), 321–339.

Tennent, R., Lockie, S., 2013. Vale Landcare: the rise and decline of community-based natural resource management in rural Australia. J. Environ. Plann. Manag. 56 (4), 572–587.

Tian, Y.H., Govindan, K., Zhu, Q.H., 2014. A system dynamics model based on evolutionary game theory for green supply chain management diffusion among Chinese manufacturers. J. Clean. Prod. 80 (1), 96–105.

Vera, I.A., Abdalla, K.L., 2006. Energy indicators to assess sustainable development at the national level: acting on the Johannesburg plan of implementation. Energy Stud. Rev. 14 (1), 11.

Wang, T., Kang, F.F., Cheng, X.Q., Han, H.R., Ji, W.J., 2016. Soil organic carbon and total nitrogen stocks under different land uses in a hilly ecological restoration area of

North China. Soil Tillage Res. 163, 176–184.

Xu, Y., Tang, Q., Fan, J., 2011. Assessing construction land potential and its spatial pattern in China. Landsc. Urban Plann. 103 (2), 207–216.

Yan, M.R., Chen, K.M., Yang, T.N., 2016. Green component procurement collaboration for improving supply chain management in the high technology industries: a case study from the systems perspective. Sustainability 8 (2), 105–121.

Yu, D., Wang, X., Yin, Y., Zhan, J., Lewis, B.J., Tian, J., Dai, L., 2014. Estimates of forest biomass carbon storage in liaoning province of northeast China: a review and assessment. PLoS One 9, e89572.

Yu, H.L., 2011. Study on the system dynamics simulation model of green supply chain management. In: 2011 2nd International Conference on Management Technology and Engineering Advances in Artificial Intelligence, vol. 1–6.

Zacharias, S., Bogena, H., Samaniego, L., et al., 2011. A network of terrestrial environmental observatories in Germany. Vadose Zone J. 10 (3), 955–973.