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Assessing sustainability of soybean supply in China: Evidence from provincial production and trade data

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A B S T R A C T

With the increasing demand and limited production, China has to import a large amount of soybeans. However, soybean has been chosen as one target of the recent trade war between the US and China. It is therefore critical to assess the sustainability of soybean supply in China. Under such a circumstance, this study aims to fill such a research gap by using an emergy accounting approach from both spatial and temporal perspectives and at provincial-level. The impact of trade war on soybean imports and production is simulated by one GTAP (Global Trade Analysis Project) model. The results of Emergy Sustainability Indices (ESI) show that it is urgent to improve the sustainability of soybean planting in Heilongjiang, while Yunnan is the most appropriate place for planting soybean. For the international supply, the EER (Emergy Exchange Ratio) of China has decreased by 72% and the decrease of EERs at provincial level ranged from 59% to 86% during 2000–2015. The simulation results indicate the necessity of adjusting spatial structure of soybean planting and applying reasonable economic instruments to encourage sustainable soybean production.

1. Introduction

China is now the largest importer of soybeans, accounting for over 60% of the world's total exports (USDA, 2018). Fostered by the growing incomes and rapid urbanization, the imports of soybeans in China is estimated to increase from 98 million tons in 2019/2020 to 126 million tons in 2028/2029 (USDA, 2019). This enormous demand on soybeans is collaboratively driven by the livestock feeding sector and domestic oil consumption (Taherzadeh and Caro, 2019). Considering the large population and the long-time preference for soybean oil among other vegetable oils, China has the highest consumption of soya oil all over the world (USDA, 2018). In addition, soybean is one major protein source for feeding pigs, further increasing the national demand. Hence, both the direct and indirect demands on soybeans contribute to the enormous consumption of soybeans, which is hard to mitigate in the near future.

Unfortunately, the unsustainable and scarce soybean supply fails to meet such a huge demand, due to less arable land, low yields and inappropriate policies. For instance, the soybean yield in China only reached 75% of the world average level (Masuda and Goldsmith, 2009; Qiang et al., 2013). Also, the implementation of

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Abbreviations

CGE	Computable General Equilibrium
EMA	Emergy Accounting
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
G20	Group of Twenty
GDP	Gross Domestic Product
GTAP	Global Trade Analysis Project
HS Code	Harmonized Commodity Description and Coding System
Sej	Solar Energy Joules
UEV	Unit Emergy Value
UN Comtrade	United Nations International Trade Statistics Database
US	United States

"Returning Farmland to Forests" policy directly decreased the arable land. Another policy, namely the "Giving Priority to Major Grains" policy, further discouraged the Chinese farmers to plant soybeans (Trac et al., 2013). Although the Chinese government is now subsidizing farmers to expand their soybean production, it is impossible to meet with the domestic demand only by domestic production in the near future (Gu and Patton, 2019).

Consequently, China has begun to rely on importing soybeans from other countries during the last decade. However, international soybean trade is being influenced by many factors, such as market crisis and tariff changes (Oliveira and Schneider, 2016; Wang et al., 2018; Zhao et al., 2010). For instance, the Chinese soybean processing companies suffered a huge loss during the soybean crisis caused by the dynamic price changes manipulated by the Chicago Board of Trade between 2003 and 2004 (Li, 2009). Particularly, the soybean import from the US has been decreased by over 30% due to the increased tariff caused by the US-China trade war since 2018. Such a political tension may be further aggravated after the US government announced its new policy on imposing a higher tariff on $200 billion worth of Chinese imports in May 2019 (Pham, 2009). Under such a circumstance, it is critical to investigate the sustainable production of soybean in China so that valuable policy insights can be obtained.

Academically, several studies have been published for uncovering the driving forces, geographical structure and price predictions of soybean trade, as well as the impact of geographical distance and trade gravity among countries (Fung et al., 2003; Wiles and Enke, 2014), while others focus on the simulation and quantitative assessment of impacts caused by trade shock imposed on agricultural products utilizing Global Trade Analysis Project (GTAP) and statistics analysis (Taheripour and Tyner, 2018; Yu and Jensen, 2014). Very recently, optimizing spatial patterns of yields by statistical analysis and spatial modeling on soybean production have also been investigated (Assefa et al., 2018; Mourtzinis et al., 2019). In addition, several Chinese scholars predicted soybean yields and planting regions, as well as how to revitalize the soybean industry in China (Liu et al., 2008; Yang et al., 2008; Jin and Zhu, 2008).

In general, these published studies are helpful to understand soybean supply from the perspectives of national and regional economy, international trade. From sustainability point of view, Brazil is a pioneer in assessing the sustainability of soya production in terms of emergy analysis to compare different production system (Ortega et al., 2005) Also, later efforts have been made to assess the fair trade, biodiesel and co-inoculation of soybean production at national/system level, while provincial analysis is still inefficient (Cavalett and Ortega, 2007; Cavalett and Ortega, 2010; Hungria et al., 2013). For the case of China, several studies focus on measuring the sustainability of soybean production, depicting temporal trends, accounting ecological footprints, and comparing different planting modes for better ecological outcomes (Qiang et al., 2013; Zhang et al., 2016; Wang et al., 2018; Liu et al., 2019a; Liu et al., 2019b; Taherzadeh and Caro, 2019). However, these studies focus on national scale or local scale, none of them focuses on provincial scale. Actually, study on provincial level is critical as provincial governments are responsible for making local agricultural policies, while the central government provides more general principles for agricultural development since China is a very large country and different provinces are facing different challenges with different resource endowments and climatic conditions. For instance, although China's reforming policy of agriculture has been adopted nationally, the local agricultural productivity is varied, and the different interpretation of national policy at provincial level even caused continuing loss of arable land in Zhejiang Province (Gong, 2018; Skinner et al., 2001). In addition, these published studies seldom consider the integration of temporal and spatial assessment and therefore cannot help generate more region-specific policies.

Under such a circumstance, this study employs both emergy accounting (EMA) and the Global Trade Analysis Project (GTAP) model for simulating China's soybean production and trade at the provincial level. EMA has been widely used to assess the supply-side values of trading commodities so that the fairness of trade and the sustainability of producing systems can be revealed (Ortega, 2005; Cuadra and Rydberg, 2006; Tian et al., 2017; Tian et al., 2018; Ali et al., 2019; Liu et al., 2019a). Covering multiple regions and diversified sectors, the GTAP model is a mainstreaming computable model to replicate and simulate the real-world economy and thus has been adopted for various kinds of economic analysis related to international trade (Britz and Hertel, 2011; Qi and Zhang, 2018; Rutten et al., 2013; Britz and Hertel, 2011). We expect that the findings from this study can provide valuable insights to those decision-makers so that appropriate policies can be made toward sustainable soybean supply. The whole paper is organized below. After this introduction section, section 2 elaborates research methods and data. Section 3 presents the research results. Section 4 discusses the policy implications. And section 5 draws research conclusions, as well as the limitations of this study.

2. Data and methods

2.1. Methods

2.1.1. Emergy accounting approach (EMA)

Emergy accounting (EMA) is to evaluate the contribution of the natural system to the human economy, namely, the assessment of "supply system of value" (Tilley and Brown, 2006). Emergy is defined as the available energy directly and indirectly utilized by the natural system to make a product or provide a service, thus representing the true value (Brown and Ulgiati, 1997; Odum, 1996). By converting into the same basis of emergy (typically expressed in solar energy joules, sej), different forms of energy, mass flows, labor and service can be unified into the united emergy flows. This conversion is accomplished through multiplying the raw inputs flows by the appropriate Unit Emergy Values (UEV). The accounting of emergy enables cumulative embodiment to be considered throughout the supply chain of trading commodities. In so doing, ecological biosphere and the economy system can be linked together to assess the objective and stable values of products in a novel way (Tian et al., 2017; Zhong et al., 2018). Consequently, EMA is suitable for evaluating the sustainability of agricultural production and the imbalance of international trade and has been applied in several studies (Ali et al., 2019; Cavalett and Ortega, 2009; Liu et al., 2019b).

For the emergy flows accounted in this study, U represents the total emergy flowing into the production system. U can be categorized into four flows, including the local renewable (R), local non-renewable (N), purchased renewable (F_r) and purchased non-renewable flows (F_n). Table 1 lists the detailed category of every flow and the UEVs, all of which have been updated to the latest emergy baseline (12E+24 sej/year) by multiplying the suitable conversion coefficients (Brown et al., 2016). Also, labor and seeds are considered as F_n instead of F_r due to the unknown percentage of R embodied, to be in line with the previous studies (Ali et al., 2019; Zhang et al., 2016). For the detailed calculation at provincial level, please refer to Table S1 in the Appendix.

Besides, Emergy-to-Money Ratio (EMR) is another fundamental indicator to measure embodied trade flows and imbalance. To connect the ecological biosphere with the economic system, EMR (sej/$) serves as the conversion fraction from emergy flows (sej) to monetary values ($), and vice versa. EMR refers to the total emergy utilized within a country divided by the annual GDP, varying every year in different nations (Odum, 1996). The annual EMRs adopted in this paper include the values of China, US, Brazil and Argentina from 2000 to 2015 (see Table S1 in the Appendix). However, only the data from 2001 to 2014 can be obtained from the National Environmental Accounting Database V2.0, the only source of successive annual EMR values (NEAD, 2017). To provide the reliable estimation of EMRs for the years 2000 and 2015, polynomial regressions have been conducted based on the time-series data from 2000 to 2014, as adopted in the previous paper (Tian et al., 2017). The parameters R^2 for the estimation of USA, Brazil, Argentina and China are, respectively, 0.74, 0.57, 0.68 and 0.84, indicating the robustness and reliability of estimated EMR values.

Emergy-based indicators are crucial for uncovering the sustainability of soybean production and the fairness of trade system. To clarify the specific concepts and corresponding indices, the sustainability of agricultural production is evaluated through Emergy Sustainability Index (ESI) by considering the system efficiency and environmental pressure (Table 2) and the fairness of trade refers to the relative trade advantage between the importer and exporter, thus specifically reflected by Emergy Exchange Ratio (EER), as generally accepted in previous emergy studies (Odum, 1996; Liu et al., 2019; Tian et al., 2018). Expressed in equation (1), the Emergy Exchange Ratio (EER) depicts the exchange of commodities, services and currencies among countries/regions, from the perspective of emergy (Rotolo et al., 2018). EER is a powerful indicator to assess the relative trade advantage between the importer and exporter. Since the traditional monetary or material flow fails to take into account the contribution of natural systems to the trading products, EER can better reveal the trade imbalance from the ecological perspective (Tian et al., 2018). Moreover, the other three indicators applied to assess the sustainability of the production system are listed in Table 2, with the detailed expressions and definitions of all indicators. Utilizing theses emergy-based indicators can provide valuable insights on the sustainability of China's soybean production and the fairness of trade.

$$EER = \frac{(\mathit{Total\ mass\ of\ traded\ good\ from\ the\ seller}(J\ or\ t)) \cdot \left(\frac{\mathit{Emergy\ of\ good\ (sej)}}{\mathit{Yield\ of\ good}(J\ or\ t)}\right)}{EMR(sej/\$) \cdot \mathit{Money\ paid\ for\ the\ good\ by\ the\ buyer}(\$)} \tag{1}$$

Table 1
The Unit Emergy Values used in this paper (Emergy baseline is 12E+24 sej/yr).

Items	Units	UEVs	References
Local Renewable Sources (R)			
Sun	sej/J	1.00E+00	Odum (1996)
Rain (Chemical potential energy)	sej/J	7.00E+03	Brown and Ulgiati (2016)
Rain (Geopotential energy)	sej/J	1.28E+04	Brown and Ulgiati (2016)
Wind (Kinetic energy)	sej/J	3.11E+03	Odum (1996)
Earth Cycle	sej/J	4.40E+04	Odum (2000)
Local Non-Renewable Sources (N)			
Net loss of topsoil	sej/J	5.61E+04	(Odum et al., 2002)
Purchased Renewable Sources (F_r)			
Irrigating water	sej/J	3.11E+04	Chen et al. (2014)
Purchased Non-Renewable Sources (F_n)			
Seeds	sej/g	5.69E+09	(Odum et al., 2002)
Labor	sej/J	5.73E+06	(Odum et al., 2002)
Machine Services	sej/$	8.34E+12	NEAD (2008)
Indirect Service	sej/$	8.34E+12	NEAD (2008)
Diesel	sej/J	1.41E+05	Odum (1996)
Electricity	sej/J	3.65E+05	Brown and Ulgiati (2004)
Pesticides	sej/g	1.89E+10	(Odum et al., 2002)
Nitrogen fertilizer	sej/g	4.84E+09	(Odum et al., 2002)
Phosphate fertilizer	sej/g	4.97E+09	(Odum et al., 2002)
Potassium fertilizer	sej/g	1.40E+09	(Odum et al., 2002)
Compound fertilizer	sej/g	3.56E+09	(Odum et al., 2002)
Plastic Mulch	sej/g	4.83E+08	Odum (1996)

Table 2
Emergy-based indicators for evaluating sustainable production system.

Indicators	Expression	Definition	References
Emergy Yield Ratio (EYR)	$U/(F_n + F_r)$	Contribution of a resource or process to the economy per unit of environmental loading	Odum (1996)
Emergy Loading Ratio (ELR)	$(N + F_n)/(R + F_r)$	Reflection of the environmental pressure from the exploitation of nonrenewable resources	Odum (1996)
Emergy Sustainability Index (ESI)	EYR/ELR	Sustainability of a system by considering the system efficiency and environmental pressure	Odum (1996)

2.1.2. The Global Trade Analysis Project (GTAP) model

The GTAP model is a computable general equilibrium (CGE) model developed by the Department of Agricultural Economics at Purdue University in the United States (US) (Hertel, 1997). One CGE model typically transforms the conceptual economic framework of a general equilibrium into a model that is computable and reasonably replicates and simulates the real-world economy. Depicting the economic mechanism using equations and data, one CGE model can be used to gain an insight into new equilibriums when the quantities and/or prices of commodities and factors get adjusted due to policies or other impacts. Regarding GTAP, the underlying microeconomic optimization framework for consumers and firms is as follows: i) consumers maximize their utility with budget constraints and fixed levels of investment and public output; ii) producers minimize their production costs when marshalling various kinds of inputs under given technology conditions (Lanz and Rutherford, 2016). At equilibrium, three benchmark identities must be met: (1) market clearance, which requires that the supply and the demand of goods or factors be balanced; (2) zero profit, under which the firms' profits are zero because the model assumes conditions of perfect competition; (3) income balance, which requires that the net income equals the net expenditure for each region.

Operationally, the GTAPinGAMS version 9 model (the GTAP model in the language of General Algebraic Modeling System) was employed for this study (Lanz and Rutherford, 2016). By default, the GTAP commodity that corresponds to "soybeans" is "osd" (oilseed crops), which covers several kinds of oilseed crops. To separate out "soybeans" from "osd" for the purpose of this study, SplitCom was used, a standard program for disaggregating commodities and/or regions in GTAP, following the fashion of Xie et al. (2018). The "osd" was thereupon split into soybeans and other oilseed crops, denoted by "soybean" and "othosd", respectively. The original 57 sectors thus become 58 sectors. To simplify the calculation so as to better focus on the sectors and regions of interest, we aggregated the 58 GTAP sectors into 19 major sectors, distinguishing agricultural commodities, agricultural and resources manufacturing, industrial manufacturing, energy and service. In particular, within agricultural commodities, the newly built "soybean" (soybeans) and "othosd" (other oilseed crops) were kept. The original 140 regions were also aggregated into 23 regions, following the scheme typically used for broad-brush analysis as set out in Lanz and Rutherford (2016), where the G20 and other regions were distinguished. The aggregation schemes for sectors and regions could be found in Table S3 and Table S4 in the Appendix, respectively.

2.2. Data sources and treatment

The data sources used in this paper include NASA Langley Research Center (LaRC)'s POWER Project (https://power.larc.nasa.gov/), Food and Agriculture Organization Corporate Statistical Database, National Environmental Accounting Database V2.0 (NEAD, 2017), China's Customs Import and Export Data (2000–2015), National Statistical Database (http://www.stats.gov.cn/english/), National Agricultural Cost-benefit Data Assembly (DP-NDRC, 2000–2016), Price Yearbooks of China, as well as our field surveys and expert interviews. Given the high concentration of China's soybean imports from three countries (the imports from Brazil, USA and Argentina comprised over 95% of the total import volume in 2015), other nations only accounted for a negligible proportion of the soybean imports (4.6%). Considering the representativeness of these major exporters and the availability of Unit Emergy Values, Brazil, USA and Argentina were chosen to conduct the import-side emergy accounting, as adopted in the previous study (Wang et al., 2018). Since the domestic trade among provinces was far less than the international imports (e.g., Shandong's soybean yields, the upper limit of trade capacity, only constituted 0.58% of the imports into this province in 2014), international imports were selected to conduct the evaluation on soybean trade regardless the neglectable domestic trade. For the research boundary at the provincial level, 30 Chinese provinces are included (excluding Macau, Hong Kong and Taiwan, and Tibet due to the lack of relevant data).

To ensure the scientific credibility of this study, Fig. 1 illustrates the necessary trade data treatment procedures. China's Customs Import and Export Data provides company-level records of trade with detailed items, values, volumes, countries of origin and destination, addresses of production and consumption, etc. To verify the accuracy, this dataset has been compared to the official database of Food and Agriculture Organization of the United Nations (FAO) in terms of China's import data of soybean from 2000 to 2015 through difference analysis (as presented in Table S1 in Appendix). The results shows that $F = 0.02$, which is far smaller than F crit (4.17) and $P = 0.90$, thus demonstrating no significant difference between FAO and the data used in this study.

For the extraction of accurate data on soybean trade, the Harmonized Commodity Description and Coding System (HS Code) was then applied for filtration. HS Code is the globally standardized

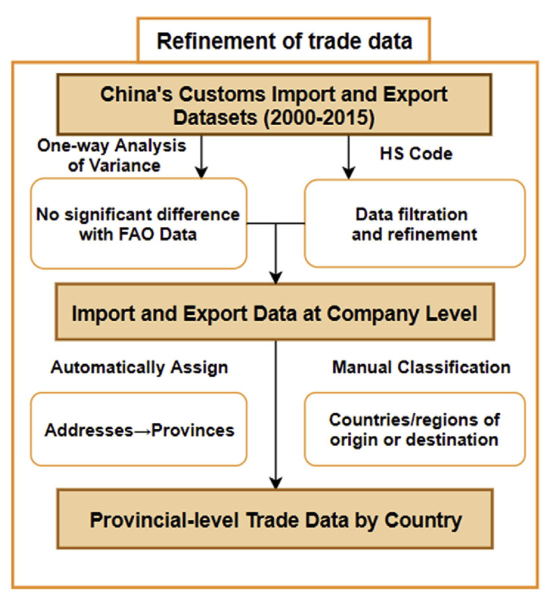

Fig. 1. Procedures of trade data treatment.

classification system of traded commodities including unique numbers and names (Ireland and Møller, 2000). The HS Codes selected in the dataset comprise 12,019,010 (yellow soybeans), 12,019,020 (black soybeans), 12,019,030 (green soybeans) and 12,019,090 (other soybeans). Soybean seeds have been excluded to eliminate the uncertainty caused by the different production processes, UEVs or tariffs. Also, duplicate and invalid records have been removed (such as those data lacking consumption addresses). Furthermore, both automatic assignment of addresses (by VLOOKUP function in EXCEL) and manual classification of countries have been conducted to generate provincial trade data. Consequently, the treated trade dataset can provide a convincible insight and cover the period of 2000–2015.

Meanwhile, the GTAP 9 database was used in this study for simulating policy impacts. As introduced in Aguiar et al. (2016), this latest database (as of May 2019) describes the world economy, covering 57 sectors/commodities and 140 regions for the reference year 2011. The GTAP 9 database includes parameters describing the behaviors of economic players. On the production side, elasticities of substitution are used between composite intermediate inputs and between primary factors. On the consumption side, the expansion and substitution in the demand system are illustrated by related parameters. Also, the parameters serve as depicting the "switch" in allocations between sluggish and mobile factors. Besides, the GTAP 9 database includes data files that consist of the monetary values of flows of goods and services, which are essential for the GTAP model. In particular, the bilateral merchandise trade activities are represented by reconciled data based on the UN Comtrade (United Nations International Trade Statistics Database) contributed by Mark Gehlhar at USDA ERS (the Economic Research Service at the United States Department of Agriculture), and the tariff data are obtained from the database of the ITC MAcMap (International Trade Center, Market Access Map, https://marketanalysis.intracen.org/MacMap.aspx) (Narayanan, 2016).

3. Results

3.1. Domestic supply: soybean production

3.1.1. Scarcity and regional disparity of domestic production

Although China has been one of the world's largest soybean consumers, the domestic supply of soybean is scarce and far from meeting the huge demand (USDA, 2018). The insufficient planting areas and the low yield further exacerbated the lack of supply. In 2015 the per hectare national yield was 1811 kg/hectare, 28% lower than the global average. In particular, soybean is land-intensive that occupies 2.5 times more virtual land resource per yield than corns (Wang et al., 2011), leading to the scarcity of arable areas. Moreover, China has an imbalanced spatial distribution of soybean planting. For instance, Heilongjiang and Henan provinces have the highest yields of soybean, while the production in Beijing was 100 times lower (only 0.63 million tons in 2015), according to the National Bureau of Statistics of China. Also, Shanghai, Hainan, and Qinghai merely have the annual yields of soybean with around one million tons, which is almost negligible compared to other major production provinces (see Fig. 2). Consequently, for the emergy accounting of soybean production system, twelve major provinces were selected due to the negligibility of other provinces and the availability of agricultural input data.

3.1.2. Emergy-based sustainability of soybean production in major Chinese provinces

The total emergy flows of provincial soybean production were calculated based upon the UEVs in Table 1, the data and EMA procedures proposed in the methods and data section. As shown in Fig. 3, the total emergy input slightly declined in 2003, then dropped again in 2007 and soon increased in 2008. Since then it had been gradually decreased until 2015. At the provincial level, Heilongjiang has the largest emergy flow as it has the largest planting areas and the third-highest UEV (as listed in Table 3). Similar to the general emergy input changing trend of the major provinces, Heilongjiang also experienced a significant drop by 36% in 2007. In this year Heilongjiang changed from a net soybean exporter to a net importer. Inner Mongolia has the second-largest emergy flow with a relatively steady growth trend, followed by Anhui with a 140% increase within 15 years. Other major provinces, such as Hebei, Jilin, Liaoning, and Hubei, experienced decreasing trends in recent years.

The total emergy input can be further categorized into four different flows, namely, Local Renewable Sources (R), Local Non-Renewable Sources (N), Purchased Non-Renewable Sources (F_n) and Purchased Renewable Sources (F_r), as classified in Table 1. Taking the year 2015 as one example, the compositions of R, N, $F_{n,}$ and F_r vary from province to province (Fig. 4). In most provinces, F_n is the major share of the total emergy flow and R is the second-largest share, while both F_r and N are relatively negligible. The predominance of F_n indicates the lack of sustainability in these soybean production provinces that highly depend on non-renewable sources from other regions. Another important emergy flow, R, including sunlight, rain, wind and earth cycle, have different relations with F_n in different provinces. For several large producers, the F_n values in Heilongjiang, Anhui and Inner Mongolia (northern and eastern regions) triple or double the corresponding R values. For other provinces, the F_n and R values almost equal in Hubei and Shannxi (middle provinces), while Yunnan (a south-western province) is an exception, with a 40% higher R than that of F_n.

Besides the temporal and spatial patterns of emergy flows at the provincial level, EMA can uncover the sustainability of provincial soybean production system through various emergy indicators. Firstly, the average soybean UEVs in different production provinces vary due to the different geographical conditions and diverse agricultural inputs (Table 3). Among the Chinese provinces, Inner Mongolia has the highest UEV (2.29E+09 sej/g), followed by Shanxi (2.03E+09 sej/g). The lowest one is Hubei (1.15E+09 sej/g), which is 40% lower than the national average UEV (1.95E+09 sej/g). Further compared with other countries, the USA has the highest one (7.50E+09 sej/g), while the UEV of Argentina is the lowest (3.77E+08 sej/g) (Odum et al., 2002). Also, the UEV of Brazilian soybeans (1.72E+09 sej/g) is close to that of Anhui and Yunnan (Cavalett and Ortega, 2009). Therefore, the soybean import from USA is more ecologically beneficial than those from Brazil and Argentina from the perspective of embodied emergy.

The evaluation of Environmental Loading Ratio (ELR) can help uncover environmental pressure induced by the investigated soybean production system. The ELR expresses the utilization percentage of environmental services in the system. Thus, a higher ELR indicates higher environmental pressure. Table 3 shows that almost all the major provinces have ELRs over 1, except for Yunnan (only 0.78). In particular, Hebei has the highest ELR of 4.55, doubling the national average ELR of 2.15 and even tripling the ELR of Brazil (1.25). From the ecological perspective, the soybean production systems in most Chinese provinces have considerable pressures on the local environment. In addition, a higher Emergy Yield Ratio (EYR) represents a higher ecological output per unit emergy purchased. In this regard, Yunnan has the highest EYR (2.33), which is double the national average (1.04) and is close to the level of Brazil (2.25). However, the ELRs in other provinces are relatively low, varying around 1.00. Consequently, the Emergy Sustainability Indices (ESI = EYR/ELR) in most provinces are low. China's national

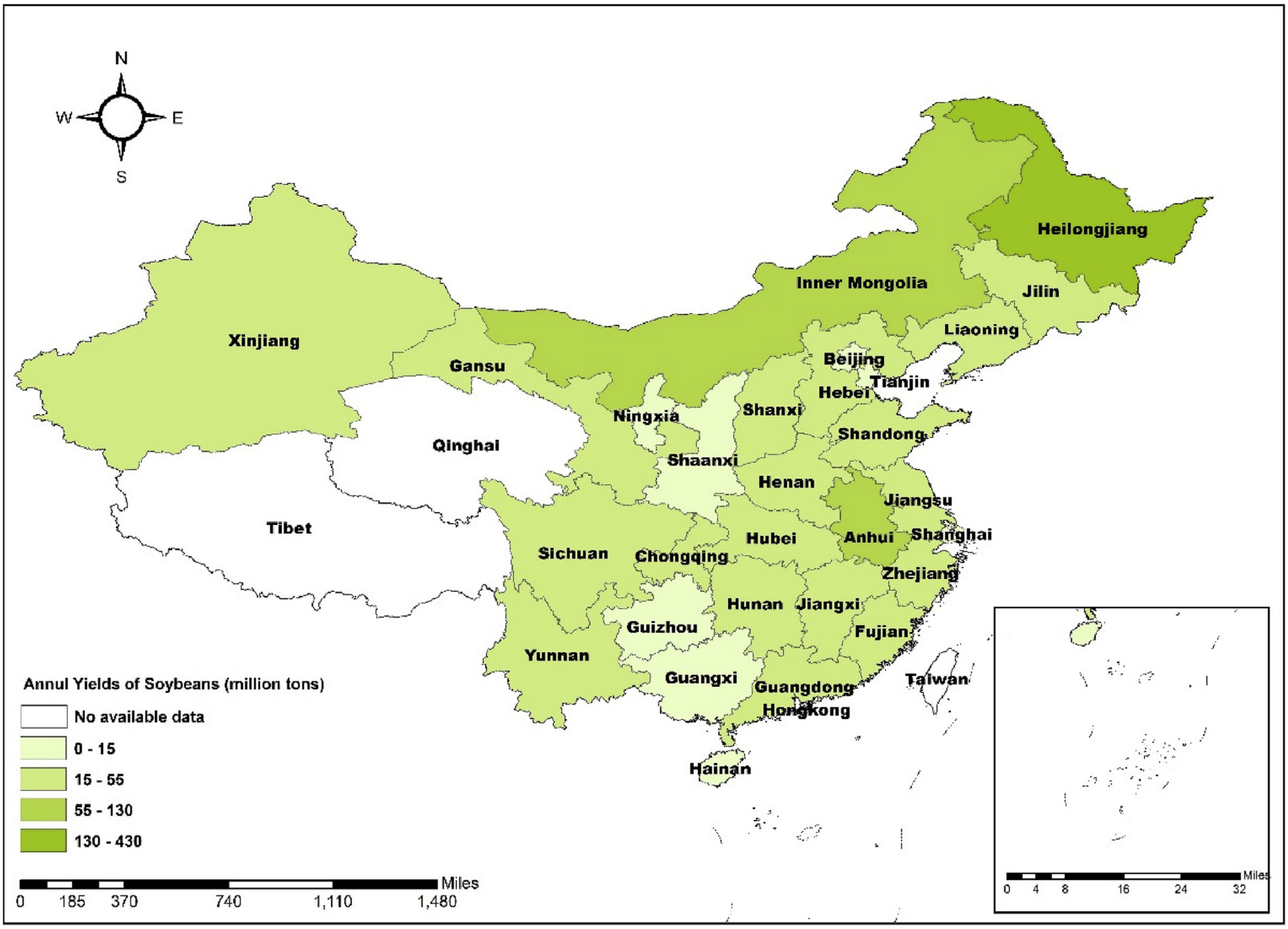

Fig. 2. Regional disparity of soybean production at the provincial level in China (2015).

average ESI is only 0.48, more than three times lower than that of Brazil, implying a significant gap between the two countries from sustainability perspective.

Among all the investigated Chinese provinces, the lowest ELR (0.87) and the second-lowest ESI (0.24) are both in Heilongjiang, the largest soybean planting province with the highest total yield. This is an alert not only to this province but also to the entire China since this province owns almost 40% of the nation soybean'

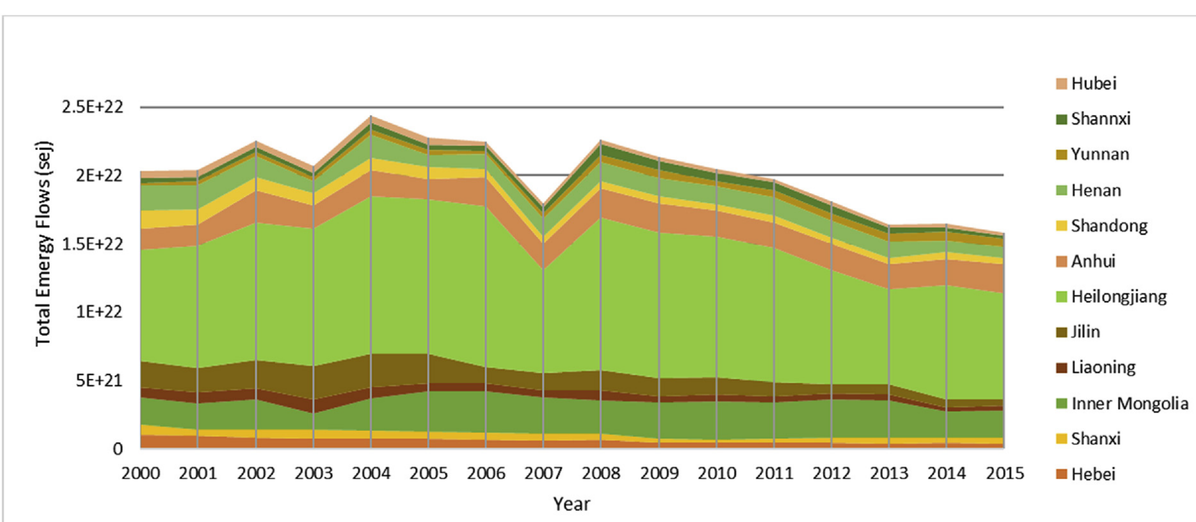

Fig. 3. Changes of total emergy input flows of soybeans production systems in major provinces from 2000 to 2015.

Table 3
Emergy indicators of soybean production in China and its major producing provinces and the comparisons with other countries (Emergy baseline is 12E+24 sej/yr).

Provinces	Hebei	Shanxi	Inner Mongolia	Liaoning	Jilin	Heilongjiang
UEV (sej/g)	1.69E+09	2.03E+09	2.29E+09	1.58E+09	1.60E+09	1.8E+09
ELR	4.55	3.40	2.50	2.50	2.86	3.56
EYR	1.04	0.93	0.96	1.02	0.95	0.87
ESI	0.23	0.27	0.39	0.41	0.33	0.24
Provinces	**Anhui**	**Shandong**	**Henan**	**Shannxi**	**Yunnan**	**Hubei**
UEV (sej/g)	1.70E+09	1.28E+09	1.59E+09	1.88E+09	1.71E+09	1.15E+09
ELR	2.48	1.97	2.31	1.73	0.78	1.50
EYR	1.06	1.27	1.18	1.35	2.33	1.49
ESI	0.43	0.64	0.51	0.78	3.01	0.99

Countries	China	Brazil [a]	USA [b]	Argentina [b]
UEV (sej/g)	1.95E+09	1.72E+09	7.50E+09	3.77E+08
ELR	2.15	1.25	–	–
EYR	1.04	2.25	–	–
ESI	0.48	1.8	–	–

[a] From Cavalett and Ortega (2009).
[b] From Odum et al., 2002. For the definitions of Emergy Loading Ratio (ELR), Emergy Yield Ratio (EYR) and Emergy Sustainability Index (ESI), see Table 2.

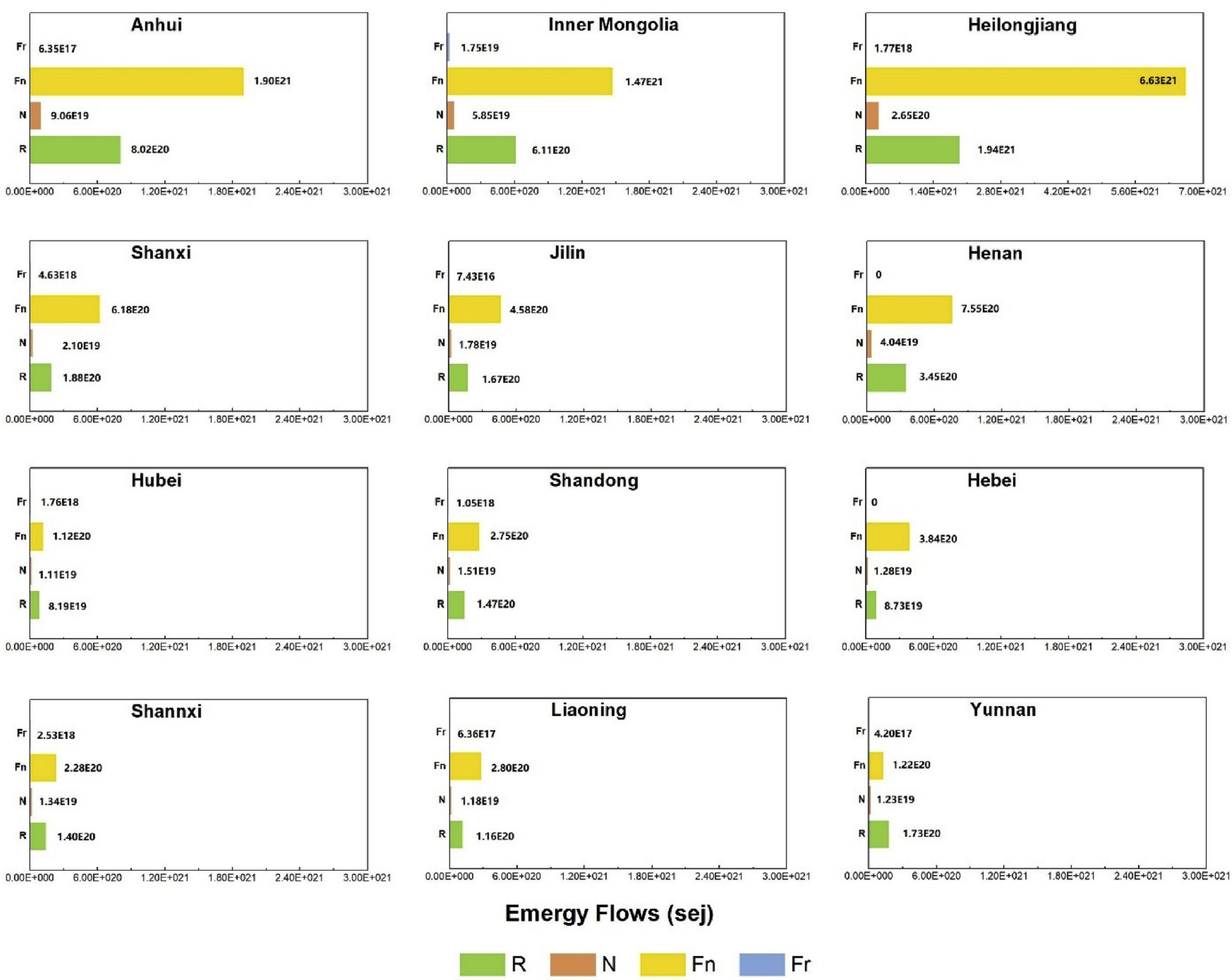

Fig. 4. Compositions of the emergy input flows in major production provinces (2015).

planting area. In contrast, although Yunnan province has relatively small soybean production (total planting area is only 5% of that in Heilongjiang), it has a leading soybean production position from an environmental perspective due to its higher ELR and ESI values.

3.2. International supply: soybean import

3.2.1. Trade deficit and the concentrated soybean supply

Over the past decades, China has become the net and the world's largest soybean importer due to the inadequate domestic supply and increasing demand (USDA, 2018; Ghose, 2014). However, the volumes of imports considerably outweighed the exports of soybeans in China and the major exporters of soybeans are highly concentrated (Fig. 5). Taking 2015 as an example (with the latest available data), China's major soybean exporters are all from the American Continent. Specifically, Brazil (49.1%), United States (34.8%) and Argentina (11.6%) contributed over 95% of the total import in 2015, while other nations merely accounted for 4.6%. Due to China's significant soybean trade deficit, this study mainly focuses on the import, rather than export.

Fig. 6 illustrates the more detailed evolution paths of soybean trade in different Chinese provinces (for the net import data of all provinces, see Table S2 in the Appendix). Notwithstanding the generally increasing trend of net import (net import = total import volume − total export volume), the growth paths are indeed diversified at the provincial level. Among the top 10 net import provinces, Shandong is the largest importer, while Beijing is the fastest growing one that has increased 42 times in just 15 years. Both Jiangsu and Guangdong had rapidly increased and then slightly reduced their soybean imports in recent years, while Hebei, Shanghai, Liaoning, Zhejiang, and Tianjin experienced steady import growth. Another key feature is that the majority of these top net importers are in coastal regions, indicating a geographical concentration.

3.2.2. Emergy analysis of soybean imports at the provincial level

Compared with the monetary flows (value) and material flows (quantity), emergy flows manifest a disparate composition of import partners (for national-level comparison among major partners from 2000 to 2015, please see Fig. S2 in Appendix). From the provincial level point of view, Table 4 shows the detailed net import quantity of emergy embodied in soybean trade in major provinces from 2000 to 2015. The net imported emergy equals the emergy embodied in soybean import minus those exported. And the emergy embodied in soybean import was accounted based on the UEVs of different countries (see Table 3), multiplied by the volumes of mass traded in all the investigated provinces. The increased emergy of imports is desired since it represents more ecological benefits received by China.

It is also clear that spatial heterogeneity exists among the major net emergy soybean importers. As one traditional soybean process province and the second-largest population province, Shandong has been the largest net importer of soybean emergy and trade volumes (Table 4), with an increasing trend from 2000 to 2014. Heilongjiang had significantly exported soybean emergy from 2000 to 2006 and then converted to a net importer in the following years with an increasing trend. Other major net importers, such as Liaoning, Hebei, and Jilin, experienced fluctuating in terms of net import emergy, but with an overall increasing trend.

Another geographical feature is that these major soybean import provinces mainly locate in the coastal zone, with time-varying patterns among different regions. Visualized in Fig. 7, it can be found that East China (like Shandong and Jiangsu) has been the hot spot area of imported soybean emergy during the studied period. Moreover, Northeast China (e.g., Heilongjiang, Jilin) had the minimum import in 2000 and then gradually increased soybean import. By contrast, South China (represented by Guangdong) experienced an increasing trend from 2000 to 2010 and then decreased their soybean import in recent years. Fig. 9 illustrates emergy flows of major soybean import provinces and the compositions of exporting countries. It is clear that at the provincial level USA is also the dominant source due to its prominent values of UEV, followed by Brazil and Argentina in most Chinese provinces, which aligns with the results at the national level (Fig. S2 in Appendix). Also, regional disparity exists in terms of importing patterns. For instance, Heilongjiang and Jilin only imported soybean from USA in 2000. Later on, these provinces began to import soybean from other countries. In this regard, Brazil has become the major soybean trade partners in several provincial markets, especially during 2010–2015.

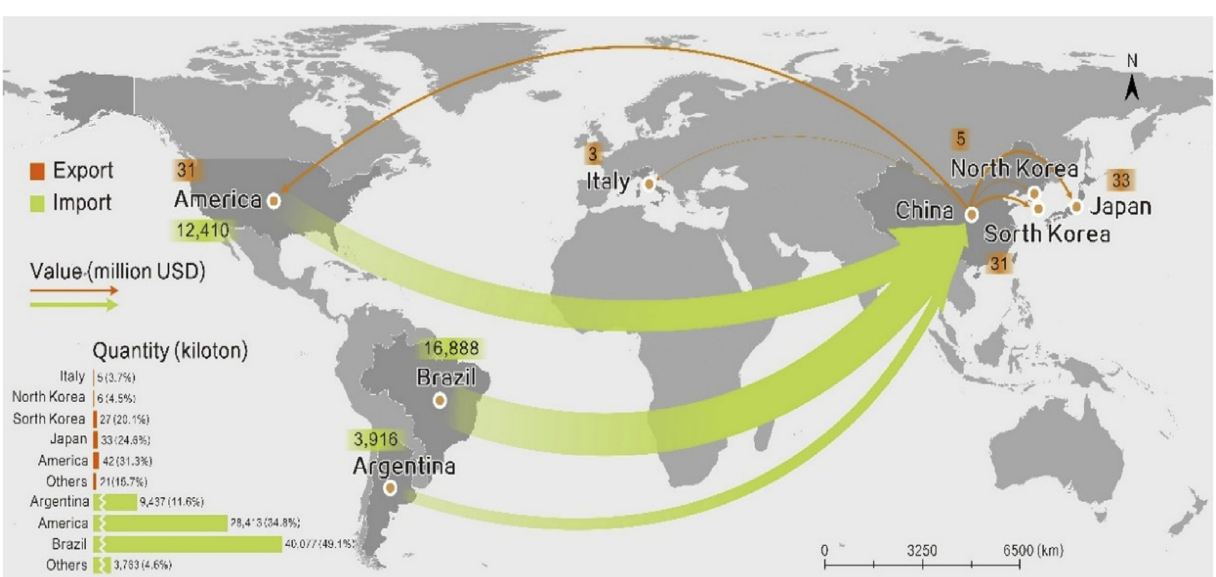

Fig. 5. China's major soybean trade partners in 2015.

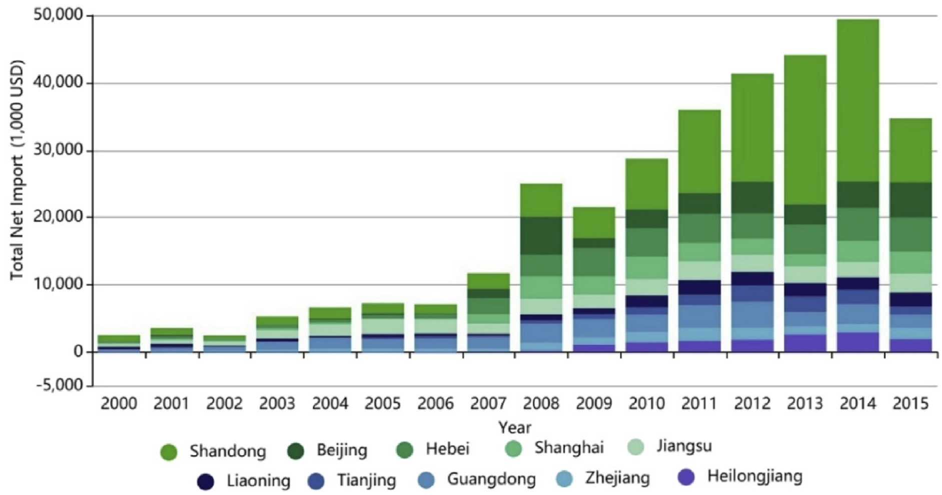

Fig. 6. Monetary net import trends of top ten Chinese provinces from 2000 to 2015. (For the monetary net imports of all provinces, see Table S2 in the Appendix).

Table 4
Net imports of emergy embodied in soybeans in major provinces from 2000 to 2015. (Units: sej).

Provinces	2000	2001	2002	2003	2004	2005	2006	2007
Jilin	2.16E+21	−8.14E+17	−6.16E+19	5.82E+20	1.26E+20	−1.02E+20	3.20E+20	2.39E+21
Liaoning	6.85E+21	6.11E+21	1.37E+21	4.34E+21	1.78E+21	4.98E+21	2.30E+21	2.92E+21
Shandong	1.07E+22	1.33E+22	5.55E+21	1.47E+22	1.68E+22	1.59E+22	1.71E+22	1.87E+22
Hebei	3.89E+21	4.62E+21	3.48E+21	5.17E+21	5.16E+21	3.88E+21	7.86E+21	1.80E+22
Heilongjiang	−2.28E+20	−2.94E+20	−3.05E+20	−2.86E+20	−3.21E+20	−3.59E+20	−3.86E+20	5.56E+20
Provinces	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Jilin	2.41E+21	5.12E+21	5.51E+21	3.33E+21	5.52E+21	4.51E+21	3.53E+21	4.79E+21
Liaoning	5.15E+21	7.86E+21	1.12E+22	1.27E+22	1.23E+22	8.82E+21	9.64E+21	1.44E+22
Shandong	2.71E+22	3.19E+22	4.55E+22	5.25E+22	7.05E+22	9.17E+22	1.03E+23	5.61E+22
Hebei	1.62E+22	2.84E+22	2.10E+22	1.73E+22	1.79E+22	1.73E+22	2.01E+22	2.16E+22
Heilongjiang	7.19E+20	6.74E+21	8.74E+21	9.57E+21	8.50E+21	9.03E+21	1.42E+22	1.25E+22

To quantitatively analyze the exchanges of emergy embodied in soybean trade between exporters and importers, the Emergy Exchange Ratio (EER) was specifically accounted for China and all the provinces with available trading data (Table 5). Overall, although the values of EER were considerably high, such values in most Chinese provinces have been substantially reduced, even for the whole country. During the study period, the EER of China decreased by 72% and the decrease of EERs at the provincial level ranged from 59% to 86%. The regional disparity exists. Yunnan, Chongqing (Southwest China), Jilin and Liaoning (Northeast China) had the highest EER values of around 20.00 in recent years, while the lowest EERs were found in Xinjiang (5.97), Guizhou (7.52) and Inner Mongolia (7.60). For the detailed figures of all regions, see Table 5.

3.3. *Simulation of trade shock on soybean supply*

3.3.1. *The trade war scenarios*

The GTAP model (the GTAPinGAMS version 9 (Lanz and Rutherford, 2016) and the GTAP 9 Data Base (Aguiar et al., 2016)) was modified to measure the impacts of "trade war" between China and the US on the soybean trade. Also, the year of 2011 was set as the baseline year. Regarding the sectors affected by the "trade war" between China and the US, the lists of Chinese products subject to an additional duty of 25% as set out in the notices released by the US government in June and August 2018 out of Section 301 investigation (USTR, 2018a; USTR, 2018b) were consulted upon for "trade war" scenarios configuration on China imports. Similarly, as for US imports, the notices released by the Chinese government in June and August 2018 as a response to the US measures, were used as the reference for "trade war" tariffs (MOF, 2018a; MOF, 2018b).

The scenarios designed in this study include two scenarios, namely, the "default" scenario and the "war" Scenario. In the default scenario, the standard tariff rates were kept from the GTAP 9 Data Base for the China-US trade. In the "war" scenario, the tariff rates were raised by an additional rate of 25% for the sectors affected by the trade war, as shown in Table S4 (Appendix). Specifically, targeting "Made in China (2025)", the US imposes an additional duty of 25% on industrial manufacturing products made in China; as for the US imports to China, except for the services, all sectors including agricultural commodities, agricultural and resources manufacturing, energy and industrial manufacturing would be subject to an additional 25% tariff rate.

3.3.2. *Impact of trade shock on trade*

The projected impact of trade shock on China's soybean imports is presented in Table 6 in details. It is clear that the value of US imports to China would drop by over 42%, whereas the Argentina and Brazilian imports to China would increase by 23% and 26%, respectively. Overall, the value of China's soybean import would decrease. From the global perspective, this will result in considerable ecological stress as the soybean production would shift from the US to Argentina and Brazil. It will induce land-use changes, leading to unintended environmental consequences. For instance, the Amazonian primary rainforests in Brazil could be under a great threat as greater demand for soybeans production may cause agricultural expansion and potentially deforestation in such land

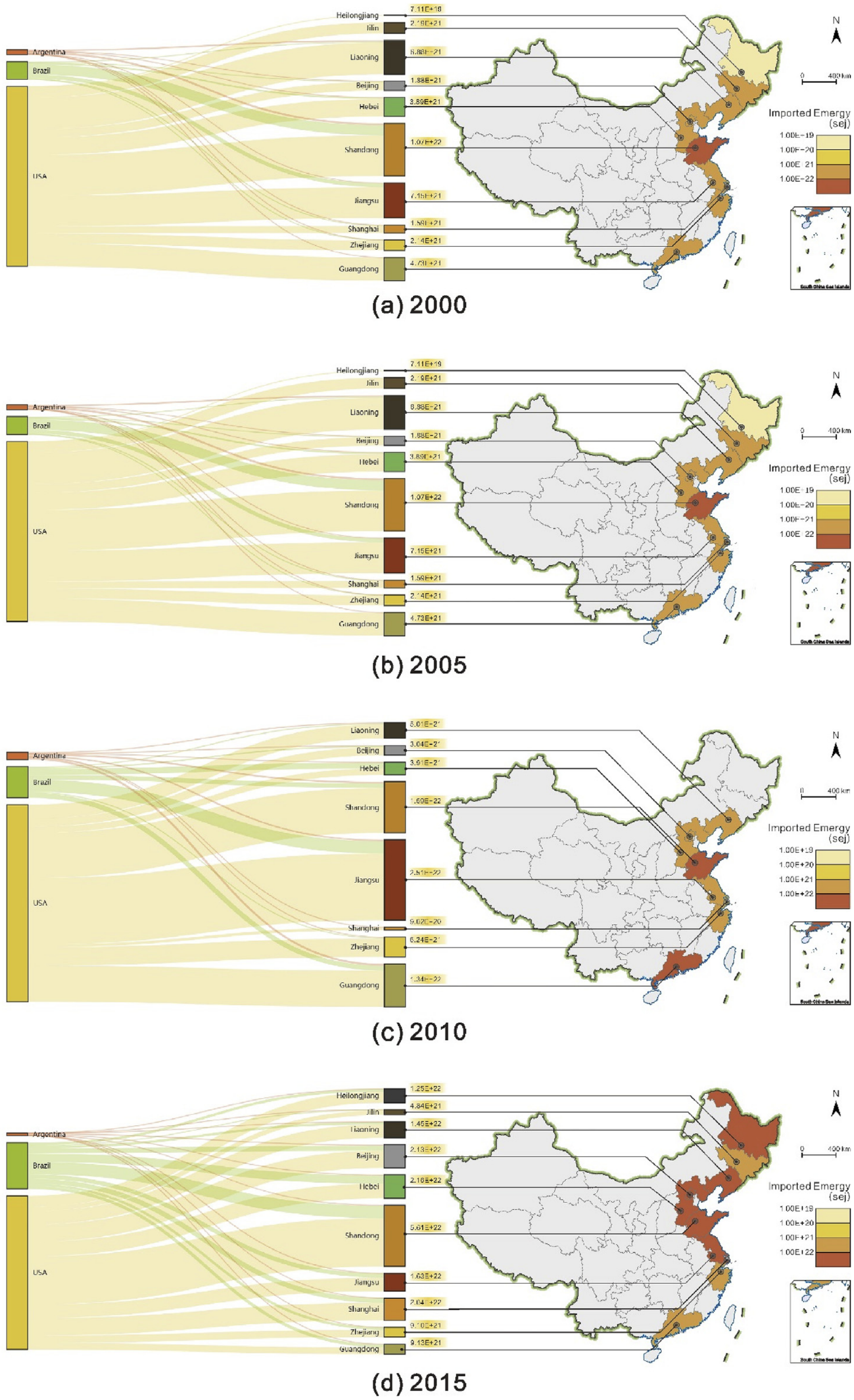

Fig. 7. Emergy flows of major soybean import provinces and the compositions of exporting countries, (a) 2000, (b) 2005, (c) 2010, (d) 2015.

(Fuchs et al., 2019).

Furthermore, Fig. 8 presents predicted soybean imports by different provinces under both the “Default” and the “War” scenarios. The provincial shares derived from actual imports calculated in this study in 2011 (as described in 2.1 Data sources and refinement) were used to scale down the total imports. Generally, all the investigated provinces would suffer from the increased tariff on soybeans. In particular, provinces in North China, such as Shandong, Hebei, and Beijing, would be the most influenced regions, while Guangdong and Guangxi in South China would also be seriously influenced.

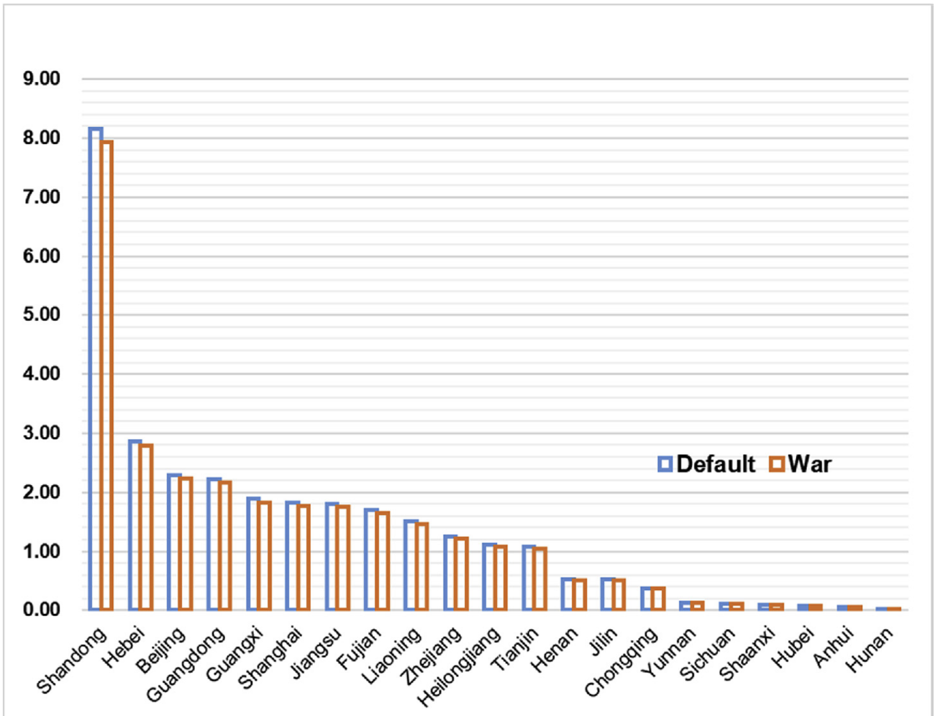

Fig. 8. Projected provincial soybean import under default and war scenarios.

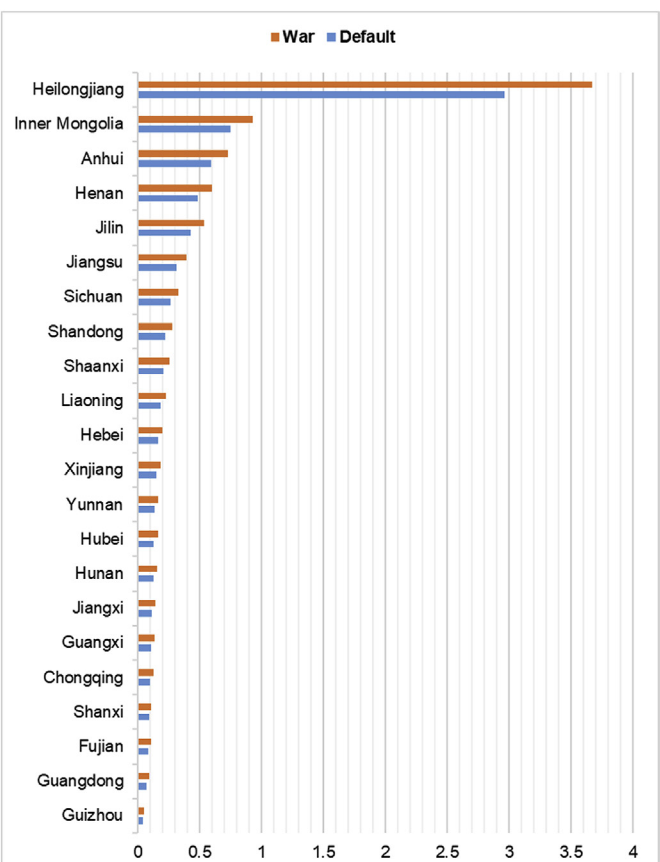

Fig. 9. Projected provincial soybean production under default and war scenarios.

3.3.3. Impact of trade shock on soybean production

Although the soybean imports would be decreased, China's domestic production may experience an increase of 23.76%, compared to the Default scenario shown in Table 7. From provincial level point of view, Heilongjiang is the top province with the highest production expansion. Other regions, such as Inner Mongolia in northeast China, Anhui and Henan in central China, would also increase their soybean production. However, such expansion may induce new ecological issues, such as land-use tensions between cropping, pasture grazing, and conservation. In short, the impact of trade shock on domestic production may aggravate environmental concerns and food security concerns, especially in major production regions.

4. Policy implications

4.1. Regional disparity of sustainable soybean supply

The results of this study identified key Chinese regions on soybean production and provide valuable insights for proposing region-specific policy suggestions. First of all, compared to the national-level emergy flow of soybean production (Fig. S4 in Appendix), most provinces presented the similar trends of fluctuation and the recent decrease since 2010. This is mainly caused by the reduced farmland for growing soybeans and it is therefore recommended to improve ecological efficiency including expanding production at lower cost of embodied emergy and reducing the use of chemical pesticide and fertilizer. Moreover, Heilongjiang, the largest soybean production province, is also the key province with the lowest ELR and the second-lowest ESI indices (Fig. 3 and Table 3). This means that this province is facing a great ecological challenge on further expanding its soybean production. On the other hand, although Yunnan province yields fewer soybeans than Heilongjiang, this southwest province has the best soybean production performance from a sustainability perspective. Therefore, it

Table 5
Emergy Exchange Ratio (EER) of soybeans imported into China and its main provinces ("-" represents no available data, for successive series of data please see Table S4 in Appendix).

Region	2000	2005	2010	2015	Growth rate of EER during 2000−2015
China	54.69	21.3	14.69	15.27	−72%
Anhui	–	–	10.93	14.37	–
Beijing	51.11	19.61	13.57	11.68	−77%
Fujian	–	20.72	17.23	15.85	–
Guangdong	76.57	18.88	14.68	13.32	−83%
Guangxi	–	17.53	13.26	11.76	–
Guizhou	–	–	–	7.52	–
Hebei	61.59	14	12.55	12.14	−80%
Henan	92.98	20.25	12.03	13.17	−86%
Heilongjiang	90.25	–	14.42	17.7	−80%
Hubei	–	8.75	13.34	11.41	–
Hunan	–	22.19	–	8.11	–
Jilin	93.23	–	18.64	19.9	−79%
Jiangsu	59.06	23.09	15.07	16.53	−72%
Jiangxi	–	–	–	17.23	–
Liaoning	51.7	4.91	14.77	19	−63%
Inner Mongolia	–	–	–	7.6	–
Shandong	41.38	22.6	15.45	16.91	−59%
Shanxi	–	41.75	30.85	7.16	–
Shannxi	–	41.6	27.77	16.5	–
Shanghai	55.48	16.89	14.96	17.83	−68%
Sichuan	51.5	16.38	11.57	13.12	−75%
Tianjin	75.77	34.85	18.81	16.53	−78%
Xinjiang	–	–	1.51	5.97	–
Yunnan	–	–	2	22.79	–
Zhejiang	65.17	7.72	15.35	16.2	−75%
Chongqing	–	37.91	12.15	20.43	–

Table 6
Projected China's soybean import by major partners under default and war scenarios.

Trading Partners	Scenarios		
	War (in billion US$ 2011)	Default (in billion US$ 2011)	(War-Default)/Default
United States	**7.222**	**12.510**	**−42.27%**
Argentina	**5.393**	**4.392**	**22.79%**
Brazil	**14.881**	**11.790**	**26.22%**
India	0.001	0.001	0.00%
Canada	0.174	0.125	39.20%
Russia	0.001	0.001	0.00%
Australia and New Zealand	0.002	0.001	100.00%
France	0	0	/
United Kingdom	0	0	/
Korea	0	0	/
Indonesia	0	0	/
Total	**28.778**	**29.629**	**−2.87%**

is recommended for this province to share their environmental-friendly experiences with the rest of China.

In addition, coastal provinces have high soybean imports due to their harbor advantages and increasing consumption. Clearly illustrated in Fig. 7, major importing provinces, including Shandong, Beijing, Shanghai, locate in the eastern coastal regions (Min and Hu, 2012; Lu, 2014). Similarly, many soybean oil extraction plants were established and operated in these regions due to lower transportation costs and advanced technologies (Chen et al., 2019).

4.2. Policy implications derived from trade shock simulation

Regarding the implications induced by the trade shock between the US and China, the simulation results suggest that the increased tariff could not only threaten the international supply of soybean but also add ecological stress on the agricultural land in China. In particular, the pastureland in Inner Mongolia could be converted to cropland to support more soybeans production. As such, soil deterioration in northeast China, especially in Heilongjiang, may further impede the expansion of soybean production. Such a reality may suggest the policymakers to consider expanding soybean production in Yunnan, where the overall soybean production has much less ecological impacts.

Economic instruments should be applied by policymakers according to local reality. One key instrument is the financial subsidy by the Chinese government (Gu and Patton, 2019). According to our

Table 7
China's projected soybeans production under default and war scenarios.

Production	War scenario	Default scenario	(War-Default)/Default
Value (in Billion US$ 2011)	9.72	7.85	23.76%

field survey in Yunnan, the most sustainable producing province discovered in our study, the economic incentives including subsidies and free organic fertilizer have been widely adopted. The interviews with local farmers showed a higher willingness for growing crops in a more sustainable way under the stimulation of financial subsides. In this regard, organic fertilizer should be promoted for soybean production, especially in the less sustainable provinces (e.g. Heilongjiang and Inner Mongolia, as suggested in section 3.1.2). However, the price of organic fertilizer is much higher than traditional chemical fertilizer. Consequently, it is recommended to increase subsidies to improve the willingness of farmers to apply organic fertilizer nationally. On the other hand, tax is another useful instrument. It is crucial for the Chinese government to reduce the tax rate for soybean production so that farmers have more economic incentives to plant soybeans. Finally, although normally imported soybean is much cheaper than the domestic soybean, the Chinese government can set up consistent sale prices for soybeans produced in various places so that domestic soybean can compete with imported soybean.

4.3. Comparison with other studies

Compared with other related studies, our results are similar to other studies, such as emergy indicators reported by Wang et al. (2011) and Liu et al. (2019). The differences are mainly due to the various emergy baselines and data sources, especially the meteorological data, UEVs and EMRs. Also, the latest studies on China's soybean trade merely focus on the national scale, without a detailed examination at the provincial level (Wang et al., 2011; Liu et al., 2019a).

From practical point of view, although Heilongjiang became a net importer in 2007, the local policies actually ban the international soybean import in order to protect the local soybean farmers. However, in the reality the headquarters of several state-owned soybean oil processing enterprises locate in Heilongjiang, but several of their soybean oil processing plants locate in other Chinese regions, such as Tianjin and Guangxi. According to the national statistical rules, such soybean oil production volumes are recorded in Heilongjiang, leading to the different statistical data and corresponding accounting results. Nevertheless, such differences are not significant and do not influence the overall accounting results.

5. Conclusions

As the largest soybean consumption country, China's domestic production cannot meet with its soaring demand and has to rely on importing soybean from other countries. The unprecedented import volume has both economic and ecological implications to the global ecosystem. However, few studies have evaluated such an impact. This paper aims to fill such a gap by employing an emergy accounting method. A further trade shock simulation is also conducted so that valuable insights can be obtained for appropriate policy suggestions. Also, both national and provincial perspectives are considered so that region-specific conditions can be addressed. Major research conclusions are drawn as below:

For the domestic supply of soybean, the emergy evolution trend of soybean production in major provinces was uncovered both temporally and spatially. The accounting results highlight the urgency for improving the sustainability and efficiency of soybean production, especially in Heilongjiang and Inner Mongolia. Yunnan province has the best performance of ESI and EYR, thus setting an ecological-friendly sample for the rest of country. For the international soybean import, both trade deficit and geographical pattern at provincial level were accounted and visualized. Also, emergy, mass, and monetary flows were compared to reveal the true values of imported soybeans. Furthermore, the EERs calculated at the provincial level present the exchanges of emergy embodied in soybean trade between exporting and importing regions. Such EER values had decreased by 72% during 2000–2015, while such values at provincial level decreased by from 59% to 86% in different provinces.

The trade shock simulation between China and the US was conducted to examine the potential effects on China's soybean import and domestic production. Not only will the value of total import decrease, but also the pattern of the source countries will experience significant changes under the high tariff policy. Argentina and Brazil will increase their absolute export values and shares, while the US will decrease their export to China. The production expansion induced by the import reduction would potentially lead to more soybean production taking place in North and Northeast China, leading to increasing ecological stress in these major Chinese provinces. It is therefore recommended that policy makers should consider using various economic instruments to improve the overall sustainability of soybean production. In addition, it is suggested that more soybean production should take place in more ecologically beneficial regions, such as Yunnan in Southwest China.

Research limitations of this paper do exist, including the lack of updated soybean UEVs in the US, Brazil, and Argentina, due to lack of relevant data. In order to solve this problem, we have to use the UEVs published in previous studies with appropriate modifications. It would be critical to update such UEVs by collaborating with researchers in these countries. Similarly, collaboration with other emerging soybean production countries, such as Russia, Ukraine, and South Africa, would be necessary so that more comparison studies can be made among different countries.

Declaration of competing interest

None.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.119006.

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