

Integrated emergy and economic evaluation of an ecological engineering system for the utilization of *Spartina alterniflora*

Hong-fang Lu ^{a, b}, Huan-shi Zhang ^c, Pei Qin ^{d, *}, Xiu-zhen Li ^{e, **}, Daniel E. Campbell ^f

^a CAS Engineering Laboratory for Vegetation Ecosystem Restoration of Island and Coastal Ecosystem, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou, 510650, China

^b Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou, 511458, China

^c Nanjing Institute for Comprehensive Utilization of Wild Plants, Nanjing, 210042, China

^d School of Life Sciences, Nanjing University, Nanjing, 210046, China

^e East China Normal University, Shanghai, 210042, China

^f US EPA, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division, 27 Tarzwell Drive, Narragansett, RI, USA

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ABSTRACT

An integrated emergy and economic evaluation of a 7-step ecological engineering system (7-step EES) located in Jiangsu Province, China was carried out. This 7-step EES was constructed to fully utilize existing *S. alterniflora* production through a low waste, clean production process and to help control the expansion of this invasive grass. First, the above ground *S. alterniflora* biomass removed for invasion control is used as the feedstock for the extraction of a bio-mineral liquid and its encapsulation, both of which provide a health supplement to treat gout and angiocardiopathy patients. Next, the residues left after extraction are used as a medium for mushroom cultivation, and then for raising earthworms. Finally, the remaining residues become the main component of a microbe enriched organic fertilizer, which is then returned to the soil. A suite of emergy indices were constructed on multiple temporal and spatial scales to examine the operation of the whole system and its subsystems. The results showed that the temporal sustainability of the 7-step EES was relatively high at different spatial scales, especially at the local scale as indicated by its EISD_{LS} (1.55E+03). Full implementation of the 7-step EES for *S. alterniflora* currently residing on the coast of China can result in a potential economic output that is greater than 2% of the national GDP, with an economic output/input ratio over 29. In addition, the 7-step EES had an environmental loading ratio lower than that of the regional system. Sensitivity analysis showed that decreasing the cost of the purchased inputs needed to make the capsules is the key problem that needs to be solved to optimize the system, both for its sustainability and economic viability, on all spatial and temporal scales.

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1. Introduction

Invasive alien species cause great environmental, social and economic impacts to global ecosystems (Olszańska et al., 2016; Zhang et al., 2019); however, so do the actions used to control them. As a result, there are often social conflicts over how to control, eradicate or utilize invasive species (Campbell et al., 2009). In spite of this wide-spread problem, there are not many research studies

that deliver quantitative, comprehensive information on the ecological economic impacts and characteristics of invasions and the activities used to control them, even though this knowledge is essential for informed environmental planning and strategy-making.

Spartina alterniflora Loisel, a herbaceous plant belonging to the *Spartina* genus of the family, Poaceae, originated on the Atlantic and Gulf coasts of North America, where it has a function in marsh-building on prograding coasts, erosion control and soil amelioration. Because of these demonstrated beneficial properties, it was introduced into China in 1979 (Chung, 2006) at a time when coastal progradation and erosion control were major problems. At the time of its introduction, the development of

* Corresponding author.

** Corresponding author.

E-mail addresses: qinpei@nju.edu.cn (P. Qin), xzli@sklec.ecnu.edu.cn (X.-z. Li).

S. alterniflora salt marsh in China provided considerable ecological benefits, especially by capturing excess sediments from watershed erosion and promoting siltation and land-building by resisting wind and wave erosion. Other benefits of this ecosystem are, fixing CO₂ to mitigate global warming (Zhang et al., 2010), providing habitat for wild animals (Wu et al., 2011), accumulating nutrients (Liao et al., 2008) in the sediments, and controlling pollution by purifying the water (Nalla et al., 2012). However, *S. alterniflora* has continuously replaced native plants, which have inundation tolerances that overlap with it, e.g. *Suaeda heteroptera*, *Phragmites australis*, *Aeluropus littoralis*, *Scirpus mariqueter*, and *Zmperata cylindrical*, which are found in the coastal marshes along the eastern and southeastern coasts of China. In its inundation zone, *S. alterniflora* is a dominant competitor due to its rapid growth, high salt tolerance, and strong reproductive capacity (Yin et al., 2015). Invading *S. alterniflora* covered a large area of mud flat along the eastern and southeastern coasts of China, at least in part, occupying the niche of the native species mentioned above, altering the mudflat habitat, changing and even diminishing biodiversity, and damaging aquaculture carried out on these intertidal lands (Qin et al., 2019). Additionally, the high siltation rate in *Spartina* areas, which is primarily caused by excess sediment supply brought in by water flows from outside that is accumulated by *Spartina* marshes, has affected the entry and exit of ships, forcing the port area to move seaward, resulting in huge economic losses and social impacts, etc. (An et al., 2007; Chen et al., 2014). Due to these negative effects, *S. alterniflora* was listed as an invasive grass by the State Environmental Protection Agency (now, Ministry of Ecology and Environment) of China in 2003 (Wang et al., 2008a). Similar threats have been reported in many other places worldwide, including the Pacific Coast of North America, Europe, and New Zealand (Feng et al., 2017; Strong and Ayres, 2016).

Many methods to control or eradicate *S. alterniflora* have been tried (Li and Zhang, 2008), including physical or mechanical methods (Hedge et al., 2003; Yuan et al., 2011), chemical techniques (Liu et al., 2004), and biological methods (Fisher et al., 2005). However, no efficient and economic solutions have been found to date. Consequently, the trend of expansion of this invasive grass has not been stopped, and in 2014 it reached 55,468 ha on China's coastal lands advancing from 3956 ha in 1990 (Fig. 1, Zhang, 2017; Zhang et al., 2017a). In addition, exotic *S. alterniflora* has been spreading throughout the world and in 2004, it was found at Great Brak Estuary, South Africa, which is the first record of this saline grass in Africa (Adams et al., 2016).

In contrast to the passive and active control methods mentioned above, some scientists have been working on developing ecological engineering systems to utilize *S. alterniflora* as a resource, e.g. as green manure (ZOLR, 1997), as fodder for livestock (Qin et al., 1998) and aquaculture (Ji et al., 1992a, b), as feedstock for biofuel and functional foods (ZOLR, 1997), and as a culture medium for mushroom growth (Qin et al., 2019). In 2014, after over two decades of development and testing, a complex 7-step ecological engineering system (7-step EES) was constructed in Jiangsu Province, China. The 7-steps in the *S. alterniflora* utilization process are 1) *S. alterniflora* harvesting, 2) product transportation, 3) biological mineral liquid (BML) extraction, 4) encapsulation, 5) mushroom cultivation, 6) earthworm-rearing, 7) microbe-enhanced organic fertilizer manufacturing. This value-added processing chain for *S. alterniflora* is abbreviated as SH-TR-BML-CAP-MUS-EW-MOF and this process allowed for a complete utilization of *S. alterniflora* harvested from the *S. alterniflora* saltmarshes in Jiangsu. The process proceeds as follows: First, the above ground biomass of *S. alterniflora* is harvested at the end of October before seed maturation and then the biomass is transported to a plant where bio-minerals are extracted

from the stock. This bio-mineral liquid is then used as a supplement to support the health of gout and angiocardiopathy patients (Qin et al., 2019). After the extraction of bio-minerals, the residues of *S. alterniflora* are transported to a farm, where they are used as a medium for the cultivation of mushrooms, and then for rearing earthworms, and finally, the remaining material is used as the main component of a microbe enriched organic fertilizer (Qin et al., 1998; Wang et al., 2008a), which is subsequently returned to the land. However, the ecological and economic characteristics of this 7-step EES have not been quantified yet, although this knowledge is essential for both the effective application and further optimization of the complex system to fully utilize *S. alterniflora*; which, in turn, can be an essential part of planning for the control of this invasive grass. Emergy evaluation was used to quantify and analyze the ecological economic properties of the 7-step EES.

In the late 1980s, H. T. Odum and his colleagues (Odum, 1986) developed the concept of emergy, which is a comprehensive, thermodynamically-based quantity that is usually expressed in solar emjoules (sej). Emergy refers to all the available energy of different kinds required to support a production process, when converted to one type of energy, e.g., solar joules¹ (Odum, 1996). All ecological and economic processes are accompanied by the transformation of energy potentials, and consequently, the value of all types of energy, materials, as well as monetary flows can be quantified on a common basis as emergy, through multiplying by the emergy per unit, or the "unit emergy value" (UEV), i.e., transformity (sej/J), specific emergy (sej/g) and the emergy/money ratio (sej/money unit). Emergy Systems Theory and the emergy method (Odum, 1996) are used to put the contributions from ecosystems and socioeconomic systems on the same basis, and when taken as a whole, these methods provide a bridge between value in nature and value in the economy (Lan et al., 2002). This approach has been widely applied in evaluating ecological-economic systems and processes at all scales (Odum, 2007), including *S. alterniflora* saltmarshes (Lu et al., 2007; Campbell et al., 2009; Liu et al., 2009) and ecological engineering systems (Zhang et al., 2000a, b; Liu et al., 2004).

After over three decades of development, emergy evaluation methods have become a well-tested tool for performing integrated evaluation of ecological-economic systems, including ecological engineering and environmental engineering systems. However, different from general production systems, ecological engineering and environmental engineering systems, have generally focused on pollution/waste reduction/utilization, which were not considered in classical emergy indices. To fill this need, a suite of indices has been proposed in the past decade, considering different aspects of impacts and costs, e.g. reducing biodiversity, harming public health, land occupation (Liu et al., 2015; Wang et al., 2018), and treatment cost (Winfrey and Tilley, 2016). However, environmental impacts and consequently sustainability are complicated temporal-spatial problems which cannot be fully indicated by any single index.

In this study, a suite of emergy evaluation indices were constructed to obtain an integrated quantification of the multiple temporal-spatial scale ecological and economic characteristics of the 7-step EES. These indices are based on a consideration of the specific environmental loads on the local system and the whole system (i.e., local and background systems) spatial scales (Brown et al., 2012; Lu et al., 2014), and the economic impacts at the annual or short-term and at the long-term temporal scale (Lu et al., 2010). Furthermore, to clarify the key subsystems and inputs for optimization, the emergy evaluation was performed at not only the level of the complex 7-step EES, but also for each of

¹ A solar equivalent joule, sej, used-up in the past is called a solar emjoule, sej, which is the unit of emergy.

its seven subsystems. Synchronously, a two-level economic analysis was carried out to explore the temporal economic viability of the 7-step EES and its 7 subsystems. Finally, an integrated energy and economic sensitivity analysis was performed at two-levels to explore system optimization.

2. Methods

2.1. Data

The 7-step EES was separated into seven subsystems, i.e. the

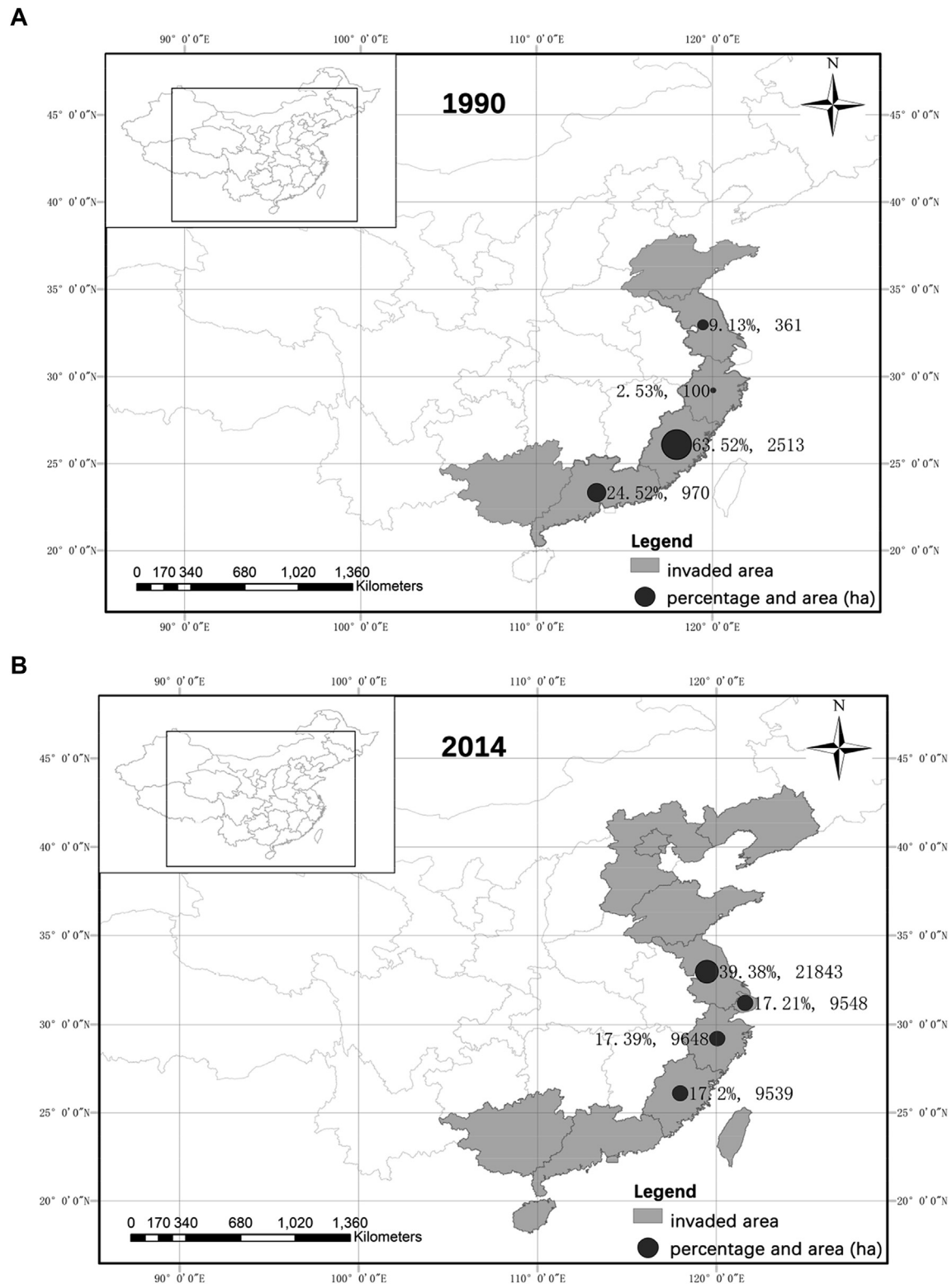


Fig. 1. The expansion of *S. alterniflora* in China from 1990 to 2014
a. The distribution of *S. alterniflora* in provinces along the coast of China in 1990
b. The distribution of *S. alterniflora* in provinces along the coast of China in 2014.

harvesting subsystem, the transportation subsystem, the extraction factory, the BML extraction subsystem, the encapsulation subsystem, the mushroom cultivation subsystem, the earthworm-rearing subsystem, and the microbe-enriched organic fertilizer manufacturing subsystem. The transportation subsystem includes the transport of harvested *S. alterniflora* to the biological mineral liquid (BML) factory and the transport of the *S. alterniflora* residues from the BML factory to the mushroom farm.

All raw data (quantities and prices) directly come from the annual records of the 7 subsystems for 2017–2018. All 7 subsystems are independent stakeholders, because they are only involved in the 7-step EES for part of the year. Consequently, only the actual cost of the particular process was counted in the analysis of that process.

2.2. Energy flows and indices

2.2.1. Energy flows

All inputs to the seven subsystems from outside the boundaries of the 7-step EES were converted to emergy (sej), based on the $1.2\text{E}+25$ sej/yr planetary solar equivalent exergy baseline (Brown et al., 2016; Campbell, 2016). All UEVs were converted to this baseline, if they were not based on it already (Bastianoni et al., 2009; Brandt-Williams, 2002; Brown and Bardi, 2001; Buenfil, 2001; Campbell et al., 2005; Campbell and Erban, 2017). Based on the observation that a linear correlation exists between real GDP and total national emergy consumption in the United States (Campbell et al., 2014), and the emergy/money ratio of China in 2005 ($9.11\text{E}+11$ sej/yuan) published by Yang et al. (2010), the emergy/money ratio of China in 2016 was deduced to be $6.10\text{E}+11$ sej/yuan, by employing the relative GDP deflator for China from 2005 to 2016 (1.49, NBSC, 2017).

Considering the specific environmental loads on the local and background systems, all inputs were classified into local renewable resources (R); local non-renewable resources (N); local wastes/pollutants (W), which are substances that would cause environmental loads to the local system, if they are not eliminated or utilized; purchased inputs, which enhance the processing capacity of the local system (F_C), but have environmental loads on the background system where they were produced, such as labor and electricity, etc.; purchased inputs causing environmental loads (F_L) on both the background system due to their production and on the local system due to their utilization, such as machines and fossil fuels etc.; and purchased waste inputs (F_W), which would cause environmental loads on the system of origin, if not being moved out or exported, for example, wastes/pollutants purchased from outside for recycling to or for use within a local system, like the *Spartina* biomass being purchased for use as the feedstock for the biological mineral liquid extraction subsystem. For sustainability analysis, W and all purchased inputs (i.e., F_C , F_L , and F_W) were further classified into renewable and nonrenewable fractions, i.e. $F_C = F_{CR} + F_{CN}$, $F_L = F_{LR} + F_{LN}$, $F_W = F_{WR} + F_{WN}$, and $W = W_R + W_N$, according to the fractions of renewable and nonrenewable inputs used during their production processes (Appendix Fig. A).

The biomass of *S. alterniflora* before harvest was defined as W_R for the harvesting subsystem and for the 7-step EES as a whole, because it is an invasive species with a suite of negative ecological and economic impacts, which were mentioned above, and because we expect it to be eradicated or controlled, if it is not utilized. In addition, there is no social or economic support for its growth in the wild (Lu et al., 2007); nevertheless, *S. alterniflora* growth promotes soil deposition instead of soil erosion or degradation (Campbell et al., 2009; Zhang et al., 2010), which is one of the desired functions of *S. alterniflora* to fulfill human purposes that is not counted in this study. The harvested *S. alterniflora* biomass is carried by

truck to the BML extraction factory. The residues of the *S. alterniflora* biomass after BML extraction are transported by truck to the mushroom cultivation facility and earthworm-rearing farms, and finally to the microbe-enhanced fertilizer manufacturing facility. The inputs of harvested biomass or residues of *S. alterniflora* to the stages in this production chain were classified as F_W , and further classified into F_{WR} and F_{WN} according to the fractions of renewable and nonrenewable inputs used during their production processes. The internal flows between the subsystems inside the system boundary were not counted as inputs to the complex 7-step EES. Consequently, the emergy input to the 7-step EES is less than the sum of the emergy inputs to the seven subsystems, and this is also true for the outputs. Ten percent of the emergy input required for labor was assumed to be renewable, F_{CR} , considering that the renewable emergy fraction of support for the Chinese economy had already decreased to 11.9% in 2005, leaving the other 90% as F_{CN} (Yang et al., 2010).

2.2.2. Emergy indices

Sustainability is an ecological economic concept with multiple temporal and spatial scale characteristics, and so its evaluation demands that these aspects of the problem be considered. The Emergy Index of Sustainable Development (EISD, Lu et al., 2010) is an emergy measure of short-term sustainability that considers the impact of market trading by incorporating the Emergy Exchange Ratios (EER) into the index formulation, which is a compliment to the ESI (Brown and Ulgiati, 1997), as a measure of long-term sustainability. The two indices should be used together to measure and understand sustainability on all time scales.

However, both ESI and EISD are temporal sustainability indicators, lacking an explicit incorporation of spatial considerations. Based on the above classification of the input flows, i.e. the actual environmental impacts of the local and purchased inputs at different spatial scales, and the economic effects of market trading on different temporal scales, a multi-temporal and multi-spatial scale emergy evaluation index system was defined (Appendix Fig. A and Table A) and calculated at both the system and subsystem levels, i.e. the definition of the complex 7-step EES, and its seven subsystems resulted in a complex evaluation of the ecological economic characteristics of this ecological engineering system.

Considering the specific environmental impacts at the local and whole system spatial scales, the local free and purchased inputs were further classified into W, F_C , F_W besides R, N and F_L , followed by the construction of ELR_{LS} and ELR_{WS} for monitoring the environmental load to the system at the local and whole system scales, respectively, extending Lu et al. (2014, 2017). In summary, we considered ESI_{LS} and ESI_{WS} to be indicators of long-term sustainability of the local system and the whole system (local plus background) scales, respectively, and the $EISD_{LS}$ and $EISD_{WS}$ to be indicators of short-term sustainability at the local and whole system scales, respectively.

2.3. Economic evaluation

A brief economic input-output analysis was done to quantify the economic viability of the complex 7-step EES and its seven subsystems. Considering that the control of invading *S. alterniflora* can be quantified based on the area covered, the net economic benefit density (yuan/ha/yr) was also calculated, and in addition, we calculated the economic output/input ratio as a measure of economic productivity of the system and its subsystems. Following the method used in the emergy evaluation, the flows between the seven subsystems were not counted in the inputs to the 7-step EES, and the internal outputs were treated similarly. Consequently, the economic inputs to and outputs from the complex 7-step EES are

also less than the sum of the economic inputs to and outputs from the seven subsystems.

2.4. Sensitivity analysis

To examine the possibilities for system optimization, a sensitivity analysis was performed for both the emergy and economic aspects of the system at two levels, i.e. for the subsystems and for specific input flows.

At the subsystem level, the sensitivity of the emergy and economic indices to the transport distance was tested by halving and doubling this distance. More exactly, the effects of changing the distance between the harvesting area and the BML extraction factory, and between the BML extraction factory and the mushroom cultivation farm, were analyzed. Since the BML can be sold and consumed directly as a health supplement without encapsulating it, and the organic fertilizer from earthworm-rearing can be sold and consumed directly without further processing to make the microbe-enhanced organic fertilizer, the effects of the use and size of the encapsulation subsystem and the microbe-enhanced organic fertilizer manufacturing subsystem on the ecological economic characteristics of the 7-step EES were also analyzed by zeroing or halving these two subsystems.

The sensitivities of the emergy and economic indices to the two main ecological economic inputs, were also tested by halving or doubling the input of deionized water to the BML subsystem and the input of capsule cells to the encapsulation subsystem.

3. Results

3.1. Emergy evaluation

An Energy Systems Language diagram of the 7-step EES (Fig. 2) was drawn to clarify the structures and processes of the system. A detailed emergy synthesis table for the complex 7-step EES and its seven subsystems is given in the Appendix Table B.

The biomass of *S. alterniflora* ($3.90\text{E}+15$ sej/yr/ha, W_R , Fig. 2 and Appendix Table B) was the largest local free emergy input to both the harvest subsystem and the 7-step EES, and it was one to four orders of magnitude higher than that of the other 6 subsystems (Table 1). The BML extraction subsystem consumed the largest share of purchased renewable emergy inputs ($89\% F_{CR}$ and $100\% F_{LR}$), considering all stages of the *Spartina* utilization system (Table 1, Fig. 3), while the encapsulation subsystem consumed the largest share of purchased nonrenewable emergy inputs that have loads on the background system, but not on the local system ($96\% F_{CN}$). The mushroom growth subsystem consumed the largest share of purchased nonrenewable inputs that have loads on both the local and the background systems ($58\% F_{LN}$). The total empower density (ED) of the complex 7-step EES was $5.92\text{E}+17$ sej/yr/ha *S. alterniflora*, with 84% and 11% of the emergy flowing directly to the encapsulation and the BML extraction subsystems, respectively (Table 1).

Detailed analysis showed that the largest purchased renewable emergy input to the BML extraction subsystem was deionized water ($5.41\text{E}+16$ sej/ha/yr, J_{20} , Fig. 2, Fig. 3 and Appendix Table B) which accounted for 89% of the purchased renewable inputs (the sum of F_{CR} , F_{WR} and F_{LR}) to the BML subsystem, and 79% of the total emergy input to the BML subsystem (Fig. 3). The largest F_{CN} was the capsule shell ($4.94\text{E}+17$ sej/ha/yr, J_{42} , Fig. 2, Fig. 3 and Appendix Table B), which accounted for 98% of the purchased nonrenewable inputs to the encapsulation subsystem and 87% of the total emergy inputs to the encapsulation subsystem (Fig. 3). The largest F_{LN} to the mushroom cultivation subsystem was facility depreciation ($4.33\text{E}+15$ sej/ha/yr, J_{58} , Fig. 2, Fig. 3 and Appendix Table B),

which accounted for 91% of the F_{LN} to the mushroom subsystem, but only 5% of the total emergy input to the mushroom cultivation subsystem. "Intro-supply" was the *S. alterniflora* culm and its residue, which was the largest emergy input to the harvesting (W_R), transportation (J_9 and J_{29}), mushroom growth (J_{36}), earthworm-rearing (J_{62}) and microbe-enhanced fertilizer manufacturing subsystems (J_{72}), respectively (Fig. 2).

3.1.1. SR, EYR, ELR and ESI

The renewable emergy supporting the biomass of *S. alterniflora* before harvesting made the harvesting subsystem over 99% self-sufficient (SR in Table 2). However, the self-sufficiency of the 7-step EES was only 0.7% due to the large amount of purchased inputs required by the other six subsystems. This condition was also seen in the big differences between the ELR and EYR of the 7-step EES and the harvesting subsystem. The EYR of the harvesting subsystem was 138 times higher than that of the complex 7-step EES, whereas the ELR of the complex 7-step EES was 5 orders of magnitude larger than that of the harvesting subsystem. As a result, the ESI of the harvesting subsystem was six orders of magnitude higher than the complex 7-step EES (Table 2).

Since they were all highly dependent on purchased emergy inputs, the ELR and EYR of the transport and the three industrial subsystems (i.e., the BML extraction, encapsulation, and microbe-enhanced fertilizer manufacturing subsystems) were all higher than $6.60\text{E}+03$ and close to 1, respectively. Even, the ELR and EYR of the two agricultural subsystems (i.e. the mushroom cultivation and earthworm-rearing subsystems) were higher than $2.85\text{E}+02$ and close to 1.002, respectively. Finally, the long-term sustainability (indicated by ESI) of the harvesting subsystem was high (up to $1.92\text{E}+04$), while those of the other six subsystems were not higher than 0.008 (Table 2).

3.1.2. ELR*

Ortega et al. (2002) defined ELR* as the ratio of all the free or purchased renewable input (considering the fractions of renewable emergy in the inputs) to nonrenewable inputs (considering the fractions of nonrenewable emergy in the inputs). Since the ELR* does not consider the specific environmental loads that are caused by these inputs, it is, in fact, an inverse indicator of the sustainability of a system, and it represents the sustainable use of all resources. Only the encapsulation subsystem had an ELR* higher than 1, and all the other six subsystems had values less than 0.5. The harvest subsystem was the most sustainable among the seven subsystems, with an ELR* less than 0.007. Without considering the specific environmental impacts resulting from the use of waste residues, but only the renewability of all the inputs, the sustainabilities of mushroom cultivation, earthworm-rearing, and microbe-enhanced organic fertilizer manufacturing (as indicated by ELR*) were all higher than that of the BML extraction and transportation subsystems (Table 2), indicating that their greater sustainability was based on their renewable emergy use.

3.1.3. ELR_{LS} , ELR_{WS} , ESI_{LS} and ESI_{WS}

Environmental loads/impacts vary in space; therefore, so does sustainability, because it depends, in part, on the environmental loads under consideration. The potential local environmental load of the 7-step EES was decreased due to the recycling or eradication of local waste loads or pollutants (W) and by enhancing local processing capacity through the utilization of purchased inputs (F_C), which help process the waste input, but cause no additional environmental load on the local system. The environmental loading of all seven subsystems and the 7-step EES at the local scale is indicated by the ELR_{LS} 's, which were much less than their ELR values (Table 2). As a result, the long-term economic sustainability

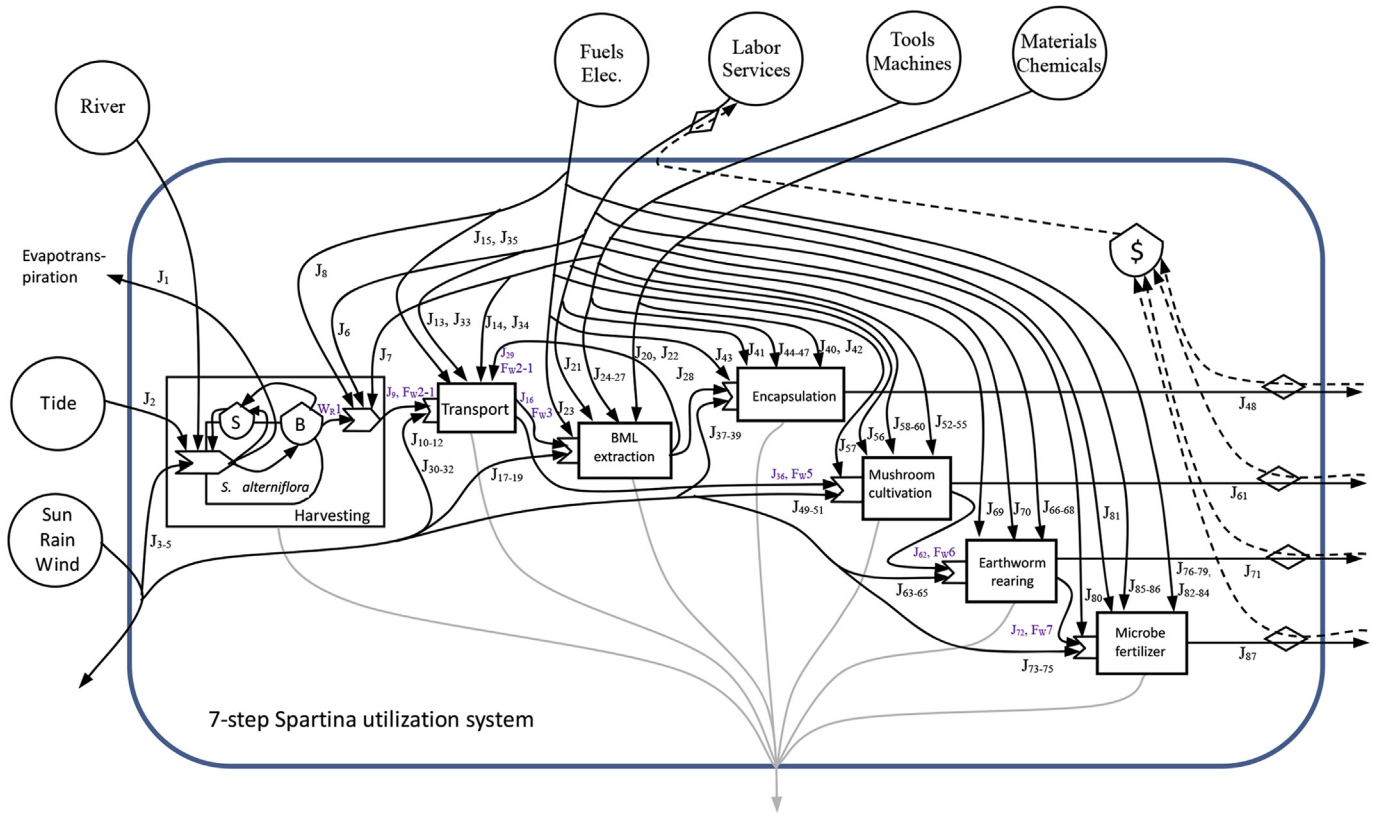


Fig. 2. Energy Systems Language diagram of the 7-step ecological engineering system for the utilization of *S. alterniflora* (Pathway labels are defined in Appendix Table B).

at the local scale (ESI_{LS}) of the 7-step EES was 4 orders of magnitude higher than the general (ESI) estimate of long-term economic sustainability.

Considering the decrease in the environmental load on the background system gained by purchasing and moving out the unwanted biomass and residues of *S. alterniflora*, all six subsystems except the harvesting subsystem had their whole system scale environmental loading ratios (ELR_{WS}) lower than their ELRs. The ELR_{WS} of the transportation, mushroom cultivation, earthworm rearing, and microbe-enhanced fertilizer manufacturing subsystems were even lower than their ELR_{LS} , with a larger fraction of F_W compared with that of F_C , which enhanced local processing capacity but caused loads on the background system. Without F_W inputs, the ELR_{WS} of the harvesting system and the 7-step EES as a whole were equal to their ELRs.

The encapsulation subsystem had the highest environmental loading and the lowest long-term sustainability at the whole system scale, but the lowest environmental loading and the highest

long-term sustainability at the local scale. Purchased inputs that were classified as F_C made up 90% of the total and these inputs had no environmental loads on the local ecosystem but did cause loads on the background system. In contrast, the harvesting subsystem had a low environmental load at both the local and whole system scales, and the highest long-term sustainability at the whole system scale, as well as the second highest long-term sustainability at the local scale following the encapsulation subsystem.

For the complex 7-step EES, 98% of purchased inputs were F_C , which enhanced local processing capacity, but did load the background system. The environmental loading ratio of the complex system at the local scale, indicated by ELR_{LS} , was only 0.1% that on the whole system scale. Consequently, the long-term sustainability of the complex 7-step EES at the local scale was $5.87E+04$ times greater than at the whole system scale. Since the *S. alterniflora* marsh was placed within the system boundary, the biomass of *S. alterniflora* is W_R for the complex 7-step EES, and because of this the environmental loading and sustainability of the complex

Table 1
Energy inputs across the system boundary to each of the subsystems and their fraction of the total input (sej/yr/ha of *S. alterniflora*).

	R		W_R		F_{CR}		F_{CN}		F_{LR}		F_{LN}		Subtotal	
	sej	%	sej	%	sej	%	sej	%	sej	%	sej	%	sej	%
Harvest	3.08E+13	5.91	3.90E+15	100.00	1.15E+12	0.00	1.04E+13	0.00	0.000	0.00	1.70E+13	0.20	3.96E+15	0.67
Transport	6.48E+10	0.01	—	—	4.39E+11	0.00	3.95E+12	0.00	0.000	0.00	4.31E+14	5.21	4.36E+14	0.07
BML	1.04E+13	1.99	—	—	5.41E+16	89.45	7.48E+15	1.45	2.90E+15	100.00	1.14E+14	1.37	6.46E+16	10.91
Encapsulation	1.04E+11	0.02	—	—	1.32E+15	2.17	4.98E+17	96.43	0.000	0.00	1.18E+13	0.14	4.99E+17	84.26
Mushroom	2.99E+14	57.49	—	—	2.60E+15	4.29	8.97E+15	1.74	0.000	0.00	4.77E+15	57.56	1.66E+16	2.81
Earthworm	1.80E+14	34.49	—	—	1.14E+15	1.88	3.53E+14	0.07	0.000	0.00	2.60E+15	31.41	4.27E+15	0.72
Microbe fertilizer	4.29E+11	0.08	—	—	1.33E+15	2.20	1.59E+15	0.31	0.000	0.00	3.39E+14	4.10	3.26E+15	0.55
Total	5.21E+14	100.00	3.90E+15	100.00	6.05E+16	100.00	5.16E+17	100.00	2.90E+15	10.00	8.28E+15	100.00	5.92E+17	100.00

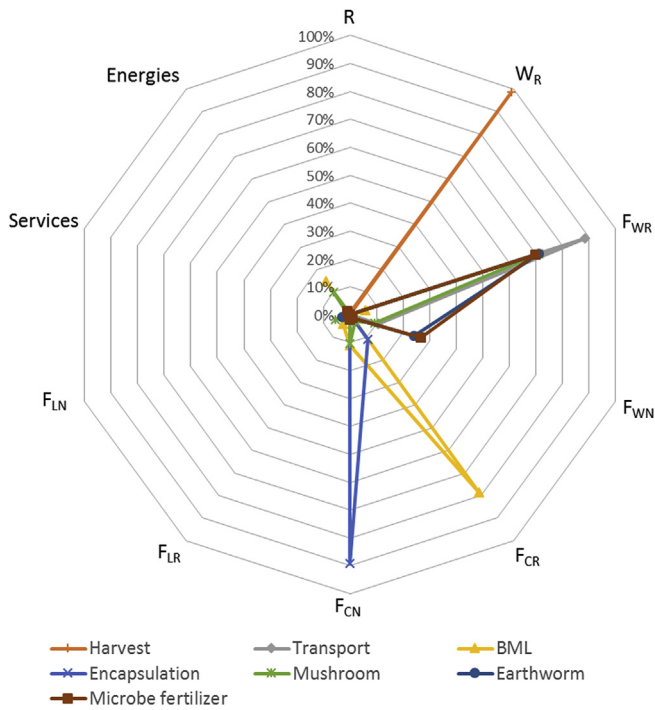


Fig. 3. Fraction of the energy inputs to each step in the 7-step ecological engineering system for the utilization of *S. alterniflora*.

system at the whole system scale, as indicated by ELR_{WS} and ESI_{WS} , are equal to the general ELR (132.93) and ESI (0.008) values (Table 2).

3.1.4. EER_i , EER_y , and EER

There are two kinds of trade for all economic systems, inputs purchased from and outputs sold to the market, with prices fluctuating around the donor prices of the products or services, but generally not equal to them. The emery exchange ratio (EER) is an indicator of the emery gained or lost through purchasing inputs

and selling outputs on the market (Odum, 1996). Specifically, the emery exchange ratio for inputs (EER_i) is defined as the emery of the products/services purchased by the system to the emery buying power of the money paid for those inputs, and the emery exchange ratio for outputs (EER_y) is defined as the ratio of the emery buying power of the money received by the system in exchange for the sale of outputs. When the indices are equal to 1, the emery embodied in the products or services received or sold is equal to the emery that can be purchased by the money paid for them. The higher the value of these indices, the higher the benefit ratio of trading for the system or process under study.

All subsystems, except the encapsulation subsystem, received a positive benefit from purchasing inputs (Table 2). The transport and harvesting subsystems had the highest and the second highest EER_i s followed by the earthworm-rearing and microbe fertilizer manufacturing subsystems, due to the economically free or low prices paid for the biomass residue of *S. alterniflora*, which has no widely known utility value in the market economy. For the same reason, considering the outputs of the subsystems, not only the transportation and harvesting subsystems and the earthworm-rearing subsystem, but also the mushroom cultivation and the microbe-enhanced organic fertilizer manufacturing subsystems had their EER_y s lower than 1. In contrast, the encapsulation subsystem had the highest EER_y , i.e. 27.23, followed by the BML extraction subsystem with an EER_y as high as 5.99. The high market values of the BML extract and the capsules due to the extract's therapeutic effects for gout and angiocardiopathy patients explain these high EER_y values. The EER_i and EER_y of the complex 7-step EES were, respectively, 1.8 and 0.96 times that of the encapsulation subsystem, which accounted for over 84% of the energy inputs to the 7-step EES, and produced its main economic output.

Defined as the multiple of EER_i and EER_y , EER is an indicator of the total emery gained or lost due to trades of both inputs and outputs. For a system or process at steady state, the emery output is equal to the emery input, then the EER is equal to the economic reward for the outputs divided by the economic cost of the inputs, i.e. the economic output/input (O/I) ratio of the system or process. Among the seven subsystems, the transport subsystem had the highest EER_i , but the lowest EER_y , while the encapsulation subsystem had the lowest EER_i but the highest EER_y . Finally, both the

Table 2
Energy flows and indices of the complex *S. alterniflora* ecological engineering system and its subsystems (/yr/ha of *S. alterniflora*).

Item	Total	Harvesting	Transportation	BML extraction	Encapsulation	Mushroom cultivation	Earthworm rearing	Microbe organic fertilizer
R (sej)	5.21E+14	3.08E+13	6.48E+10	1.04E+13	1.04E+11	2.99E+14	1.80E+14	4.29E+11
W_R (sej)	3.90E+15	3.90E+15	—	—	—	—	—	—
F_{WR} (sej)	—	—	6.49E+16	3.93E+15	—	6.10E+16	6.39E+16	6.52E+16
F_{CR} (sej)	6.05E+16	1.15E+12	4.39E+11	5.41E+16	6.23E+16	2.60E+15	1.14E+15	1.33E+15
F_{LR} (sej)	2.90E+15	—	—	2.90E+15	—	—	—	—
F_{WN} (sej)	—	—	7.85E+15	2.31E+14	—	8.06E+15	2.18E+16	2.47E+16
F_{CN} (sej)	5.16E+17	1.04E+13	3.95E+12	7.48E+15	5.06E+17	8.97E+15	3.53E+14	1.59E+15
F_{LN} (sej)	8.28E+15	1.70E+13	4.31E+14	1.14E+14	1.18E+13	4.77E+15	2.60E+15	3.39E+14
Y (sej)	5.92E+17	3.96E+15	7.32E+16	6.88E+16	5.68E+17	8.57E+16	9.00E+16	9.32E+16
SR	0.007	0.993	8.86E-07	1.51E-04	1.83E-07	0.003	0.002	4.61E-06
EYR	1.008	139.182	1.000	1.000	1.000	1.004	1.002	1.000
ELR	132.928	0.007	1.13E+06	6.62E+03	5.47E+06	285.093	499.607	2.17E+05
ELR*	7.730	0.007	0.128	0.128	8.116	0.341	0.380	0.401
ELR _{LS}	0.019	0.004	1.64E+04	0.117	2.09E-05	6.219	52.772	30.879
ELR _{WS}	132.928	0.007	0.006	15.480	5.47E+06	0.236	0.048	0.036
ESI	0.008	1.92E+04	8.86E-07	1.51E-04	1.83E-07	0.004	0.002	4.61E-06
ESI _{LS}	52.359	3.24E+04	6.09E-05	8.582	4.79E+04	0.161	0.019	0.032
ESI _{WS}	0.008	1.92E+04	167.06	0.065	1.83E-07	4.260	21.013	27.570
EER_i	1.135	19.741	32.905	7.615	0.625	6.403	11.543	11.461
EER_y	26.060	0.385	0.060	5.987	27.229	0.158	0.118	0.124
EER	29.582	7.600	1.979	45.588	17.025	1.014	1.366	1.423
EISD	0.224	1.46E+05	1.75E-06	0.007	3.11E-06	0.004	0.003	6.55E-06
EISD _{LS}	1.55E+03	2.46E+05	1.21E-04	3.91E+02	8.16E+05	0.164	0.026	0.046
EISD _{WS}	0.224	1.46E+05	330.672	2.945	3.12E-06	4.319	28.709	39.239

harvesting and encapsulation subsystems had a relatively high EERs, but they were lower than that of the BML extraction subsystem (45.59). For the complex 7-step EES, both the EER_i and EER_y were between the value of the BML extraction and the encapsulation subsystems, and its EER was 0.65 and 1.74 times that of these two subsystems, respectively.

3.1.5. $EISD$, $EISD_{LS}$ and $EISD_{WS}$

The emergy index of sustainable development (EISD) indicates the short-term economic sustainability of the system/process by considering market effects on the emergy balance of trade (as indicated by EER). This index complements ESI, which is an indicator of long-term economic sustainability.

Due to their high EERs, the short-term economic sustainability ($EISDs$) of the harvesting subsystem and the complex 7-step EES were 7.6 and 29.6 times that of their ESIs, respectively (Table 2). The $EISDs$ of the other six subsystems were also higher than their ESIs, but by a small amount (≤ 0.007).

Besides temporal characteristics, sustainability also has spatial characteristics. $EISD_{LS}$ is defined as the ratio of EYR to ELR_{LS} and it is an indicator of short-term economic sustainability at the local scale, while $EISD_{WS}$ is an indicator of short-term economic sustainability at whole system scale (local and background systems). By considering the effects of purchased inputs on the local environmental processing capacity, the short-term economic sustainability of the complex 7-step EES and its seven subsystems at the local scale as indicated by the $EISD_{LS}$ values were all higher than their temporal economic sustainabilities at the large scale, as indicated by their $EISD_{WS}$ values. The harvesting subsystem had both general and large-scale economic sustainability as indicated by its ESI, ESI_{WS} , $EISD$, and $EISD_{WS}$, with values three to eight orders of magnitude higher than those of the other six subsystems. Also, its local economic sustainability as indicated by ESI_L and $EISD_L$, was only a little less than that of the encapsulation subsystem for which 90% of the purchased inputs were F_C . The main reason behind these differences is that a large fraction of the inputs to the harvesting subsystem is contributed by W_R , the biomass of *S. alterniflora*.

Finally, the $EISD_{LS}$ of the complex 7-step EES was 1548.89, or four orders of magnitude higher than its $EISD_{WS}$ (0.22), which was equal to its $EISD$, and was six orders of magnitude higher than its ESI and ESI_{WS} (0.008, Table 2).

3.1.6. Sensitivity analysis

The transport subsystem was the main producer of wastes in the 7-step EES, thus the sensitivity of the system indices to this subsystem was examined. At the subsystem level, halving the transport distance did not cause over a 5% difference in the input flows and indicators of the complex 7-step EES (Fig. 4, and Appendix Table C). Similarly, doubling the transport distance only caused a 5% increase in F_{CN} . The microbe-enhanced organic fertilizer manufacturing subsystem was one of the four labor intensive, but lower emergy density subsystems, and zeroing out or halving the value of this subsystem did not cause over a 5% decrease in all input flows and indicators of the complex 7-step EES.

In contrast to the transportation subsystem and the microbe-enhanced organic fertilizer manufacturing subsystem, the size of the encapsulation subsystem had more fundamental effects on the ecological-economic characteristics of the complex 7-step EES. Zeroing out the encapsulation subsystem caused over a 96% and 85% decrease in F_{CN} and ELR , respectively, which results in long-term sustainability of the complex 7-step EES increasing 5.90 times (as indicated by ESI and ESI_{WS} , Fig. 4, and Appendix Table C). Similarly, halving the encapsulation subsystem caused over a 48% and 42% decrease in F_{CN} and ELR , respectively, and this results in a 75% increase in the long-term sustainability of the complex 7-step

EES at both the general and the whole system scale as indicated by ESI and ESI_{WS} (Fig. 4, and Appendix Table C).

However, due to its negative effect on EER_y , zeroing out the encapsulation subsystem caused over a 45% decrease in the EER, and consequently a 278% increase in $EISD$, and a 71% increase in $EISD_{WS}$, respectively. In contrast, at the local spatial scale, zeroing out the encapsulation subsystem caused ELR_{LS} to increase 6.07 times, accompanied by a 92% decrease in short-term sustainability as indicated by $EISD_{LS}$. Halving the encapsulation subsystem caused a 75% increase in ELR_{LS} , and a 44% decrease in the short-term sustainability.

The sensitivity of the system to the environmental input flows was also examined by halving the deionized water input to the BML extraction subsystem, which caused a 45% decrease in F_{CR} and a 5% increase in $EISD$, but did not cause over a 5% change in the other inputs and indicators. However, doubling the deionized water input to the BML extraction subsystem caused an 89% increase in F_{CR} and an over 9% increase in the emergy density (ED) and the ELR accompanied by over an 8% decrease in overall economic sustainability (i.e., ESI and $EISD$) and sustainability at the whole system scale as indicated by ESI_{WS} and $EISD_{WS}$. The same increase in deionized water input resulted an over 8% decrease in the environmental load (ELR_{LS}) accompanied by an increase of over 8% in both short-term and long-term sustainability of the subsystem at the local scale, as indicated by ESI_{LS} and $EISD_{LS}$ (Fig. 4, and Appendix Table C).

The capsule cell input was the largest purchased input to the complex system; and therefore, it had a great effect on all the ecological-economic characteristics of the 7-step EES. Halving the capsule cell input caused a decrease of over 41% in F_{CN} , ED, ELR and ELR^* of the 7-step EES, but it caused an increase of over 71% in ELR_{LS} and EER. Consequently, halving the capsule cell input caused a 73% and 228% increase in the sustainability of the 7-step EES, in general, and at the whole system scale as indicated, respectively, by ESI and $EISD$, and by ESI_{WS} and $EISD_{WS}$. Also, halving the purchased capsule input caused a 42% decrease in the long-term sustainability of the 7-step EES at the local scale as indicated by ESI_{LS} , but a 9% increase in its short-term sustainability at the local scale as indicated by $EISD_{LS}$. In contrast, doubling the purchased capsule cell input caused an increase of 83% in F_{CN} , ED and ELR , but a decrease of 45% in ELR_{LS} and EER. Doubling the purchased input to the capsule cell subsystem resulted in a decrease of 46% in long-term and short-term sustainability (ESI, $EISD$), and a decrease of 72% in these same variables at the whole system scale, as indicated by ESI_{WS} and $EISD_{WS}$. Also, doubling the purchased capsule cell input resulted in an increase of 84% and a decrease of 5% in long-term and short-term sustainability at the local scale, as indicated by ESI_{LS} and $EISD_{LS}$, respectively (Fig. 4, and Appendix Table C).

3.2. Economic analysis

3.2.1. Economic input and output analysis

Taking the 7-step EES as a black box, the economic cost density was $8.55E+05$ yuan/ha/yr, with 95% of the cost flowing to the encapsulation subsystem (Table 3). Detailed cost analysis showed that the largest economic cost for an input from outside the system was for the capsule shell ($8.10E+05$ yuan/ha/yr), which is 1.2 times that of the key material input, i.e. BML (Appendix Table B). The BML extraction subsystem had the second highest economic input density coming directly from outside the complex 7-step EES, which was $1.08E+04$ yuan/ha/yr or 1% of all economic inputs to the complex system. In contrast to our findings for the encapsulation subsystem, all the direct economic inputs to the BML extraction subsystem were from outside the complex system and were less than the value of the *S. alterniflora* biomass received from the

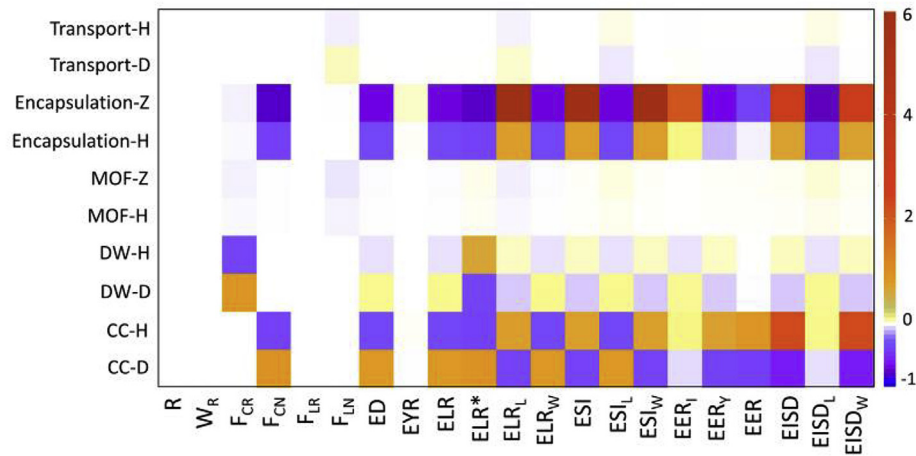


Fig. 4. Emergy-based sensitivity analysis of the 7-step ecological engineering system for the utilization of *S. alterniflora*.

H-Half; D-Double; Z-Zero; MOF-Microbe Organic Fertilizer subsystem; DW-Deionized water used in the BML extraction subsystem; CC-Capsule cell inputs to the encapsulation subsystem.

Table 3

Economic inputs across the system boundary to each of the subsystems and their fractions of the total inputs (yuan/yr/ha of *S. alterniflora*).

	F _{CR}		F _{CN}		F _{LR}		F _{LN}		Subtotal	
	yuan	%	yuan	%	yuan	%	yuan	%	sej	%
Harvest	30.00	0.23	270.00	0.03	0.00	0.00	28.95	0.22	328.95	0.04
Transport	15.26	0.12	137.38	0.02	0.00	0.00	756.50	5.62	909.14	0.11
BML	3225.00	24.70	4995.00	0.60	2400.00	100.00	186.57	1.39	10806.57	1.26
Capsule	2196.00	16.82	811794.00	97.95	0.00	0.00	19.42	0.14	814009.42	95.17
Mushroom	2427.13	18.59	6538.89	0.79	0.00	0.00	7745.81	57.53	16711.83	1.95
Earthworm	2820.90	21.60	2302.43	0.28	0.00	0.00	4263.75	31.67	9387.07	1.10
Microbe fertilizer	2343.70	17.95	2762.91	0.33	0.00	0.00	463.75	3.44	5570.36	0.65
Total	13057.99	100.00	82880.60	100.00	2400.00	10.00	13464.75	100.00	855323.34	100.00

transport subsystem (4000 yuan/ha/yr), i.e., the deionized water (2850 yuan/ha/yr), the biomass fuels (2400 yuan/ha/yr) and the electricity (1620 yuan/ha/yr, [Appendix Table B](#)).

Among the seven subsystems, the encapsulation subsystem had the highest economic input and output densities (1.49E+06 yuan/ha/yr, and 2.54E+07 yuan/ha/yr) as well as the highest net economic benefit density (2.39E+07 yuan/ha/yr). The second largest values of these economic variables were contributed by the BML extraction subsystem ([Table 4](#)). The BML extraction subsystem had the highest output/input (O/I) ratio (45.59), followed by the encapsulation subsystem (17.02). The mushroom cultivation subsystem had an O/I ratio of 1.01 and the lowest economic benefit density (2.81E+02 yuan/ha/yr) of all seven subsystems; nevertheless, a positive net economic benefit was gained from the investment.

Finally, without counting the flows between the seven subsystems, the total economic input and output densities across the system boundary flowing to and from the 7-step EES were, respectively, 8.58E+05 yuan/ha/yr and 2.54E+07 yuan/ha/yr, accompanied by a net economic benefit density of 2.45E+07 yuan/ha/yr, and an output to input (O/I) ratio of 29.6 ([Table 4](#)).

3.2.2. Sensitivity analysis of the economic subsystems and flows

At the subsystem level, both halving and doubling the transportation distance and halving and zeroing out the microbe-enhanced organic fertilizer manufacturing subsystem did not cause over a 5% difference in the economic input, output, benefit density, or O/I ratio of the 7-step EES. In contrast, halving and zeroing out the encapsulation subsystem, respectively, caused 47% and 95% decreases in the economic input, 49% and 97% decreases in the economic output, and consequently 49% and 97% decreases in the economic benefit density of the 7-step EES ([Fig. 5](#), and [Appendix Table D](#)). Halving the size of the encapsulation subsystem did not cause over a 5% difference between the economic O/I ratios, but zeroing out this subsystem caused a 45% decrease to the economic O/I ratio of the 7-step EES.

With respect to the input flows, halving and doubling the deionized water input to the BML extraction subsystem did not cause over a 5% difference in the four economic characteristics of the complex 7-step EES. In contrast, halving and doubling the capsule cell input to the encapsulation subsystem, respectively, caused a −47% and a +94% change in the economic input, and a +89% and −49% change in the economic O/I ratio of the complex

Table 4

Economic flows and indices of the 7-step ecological engineering system for the utilization of *S. alterniflora* and its subsystems (/yr/ha of *S. alterniflora*).

Item	Total	Harvesting	Transportation	BML extraction	Encapsulation	Mushroom cultivation	Earthworm rearing	Microbe organic fertilizer
Input (yuan)	8.58E+05	3.29E+02	3.41E+03	1.48E+04	1.49E+06	2.02E+04	1.14E+04	1.20E+04
Output (yuan)	2.54E+07	2.50E+03	6.75E+03	6.75E+05	2.54E+07	2.05E+04	1.56E+04	1.71E+04
Benefit density (yuan)	2.45E+07	2.17E+03	3.34E+03	6.60E+05	2.39E+07	2.81E+02	4.19E+03	5.07E+03
Output/input ratio	29.58	7.60	1.98	45.59	17.02	1.01	1.37	1.42

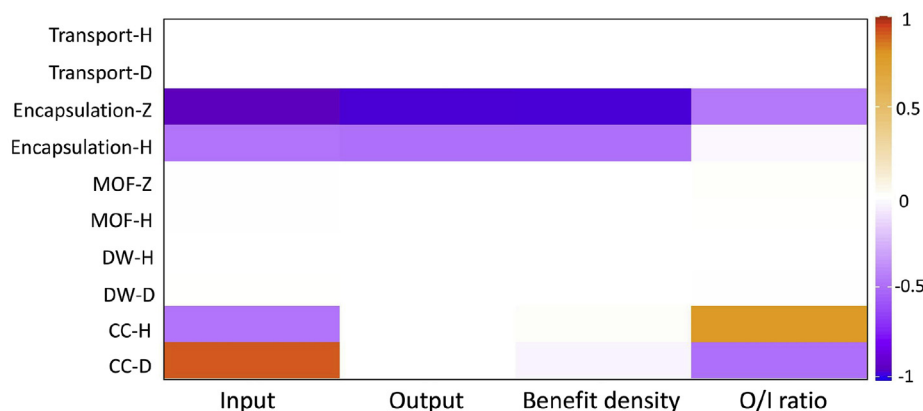


Fig. 5. Economic sensitivity analysis of the 7-step ecological engineering system for the utilization of *S. alterniflora*. H-Half; Z-Zero; D-Double; MOF-Microbe Organic Fertilizer subsystem; DW-Deionized water used in the BML extraction subsystem; CC-Capsule cell inputs to the encapsulation subsystem.

system, without significantly affecting the economic benefit density (Fig. 5, and Appendix Table D).

4. Discussion

S. alterniflora was introduced into the east coast of China to trap excess sediment and consequently build new land, while protecting sea shore banks from erosion (Chung, 2006), and it worked well for these purposes (Zhang et al., 2017b; Zheng et al., 2018). However, its unexpected rapid expansion on China's coast brought a suite of negative effects, where it occupied former mudflat habitat and some areas formerly used for aquaculture on tidal lands (Li et al., 2009). The cost for control and managing this invasive grass proved to be high, e.g. the cost of its management was reported to be as high as 500 US\$/ha/yr in Chongming Dongtan Nature Reserve, Shanghai, China (Yuan et al., 2011).

The complex ecological engineering system is different from the passive and expensive physical (Patten, 2002; Chen et al., 2014), chemical (Kilbride et al., 1995; Patten, 2002), and biological control technologies (Wu et al., 1999; Grevstad et al., 2003) employed by many for controlling *S. alterniflora*, because it turns the troublesome grass into a useful resource. This system allows the complete use of the resource by passing it through the 7-step EES, i.e. first as the feedstock to make a health supplement, then as the medium for mushroom cultivation and earthworm-rearing, and finally as the main component of a microbe-enhanced organic fertilizer.

The 7-step EES results in completely eliminating waste from the harvested grass, thus making *Spartina* harvesting a cleaner production process. In this case, it is a zero-waste process with respect to the harvested *Spartina* grass. However, overall the local process produces gaseous wastes from the transportation subsystem, and thus, at the local level it is low waste production process. Waste is also produced at the larger system scale in manufacturing the inputs used by the 7-step EES, especially for the extraction and encapsulation subsystems. To balance these waste flows on the larger scale, considerable benefits to society are provided by controlling the expansion of this invasive grass in places where it is having detrimental effects on the coastal zone.

However, for the 7-step EES to become a practical solution to help solve the *S. alterniflora* problem, it needs to be sustainable and feasible from both ecological and economic perspectives, and competitive with other land use options in the region. The *S. alterniflora* harvesting subsystem is the only subsystem that is currently operating in the coastal and estuarine areas of Jiangsu Province. Compared with other general land use practices, e.g.

aquaculture, tourism, orchards and other cultivation systems, practiced in similar areas, the *S. alterniflora* harvesting subsystem has a much higher EER (7.600) and a lower ELR (0.924) (Table 5). Consequently, the *S. alterniflora* harvesting subsystem analyzed here had a long-term economic sustainability ($ESI = 1.92E+04$), which was six orders of magnitude higher than that of the above-mentioned ecological-economic systems of the beach/estuarine areas of Southeast China (Wang et al., 2008b; Li et al., 2011; Lu et al., 2009, 2017). Furthermore, its ESI is, respectively, 4 and 3 orders of magnitude higher than that of the Yancheng Biosphere Nature Reserve (5.96, Lu et al., 2007), and the Maipo mangrove marshes (23.24, Qin et al., 2000). In contrast, the economic benefit density (EBD) of the *S. alterniflora* harvesting subsystem was one to two orders of magnitude lower than the other ecological-economic systems found in similar areas.

This shortfall in the economic benefit density was made up by the next six subsystems of the 7-step EES. The economic benefit density and economic O/I ratio of the 7-step EES was found to be one order of magnitude higher than that of the above-mentioned systems found in similar coastal/estuarine areas. Consequently, the temporal sustainability of the 7-step EES was higher than most of the other ecological-economic systems, when evaluated at different spatial scales as indicated by its EISD (0.224) and $EISD_{15}$ ($1.55E+03$). The trade-off for this superior economic viability is a relatively high environmental loading ratio ($ELR = 132.93$), and consequently a relatively low long-term sustainability at the whole system spatial scale, as indicated by the values of ESI (0.008), and ESI_{WS} (0.008), which were lower than all the above-mentioned ecological economic systems found in similar coastal/estuarine areas (Table 5). One thing that needs to be clarified is that the other six subsystems that comprise the 7-step EES are located outside the coast/estuary area. Furthermore, the ELR of the 7-step EES is still relatively low compared with that of Shanghai ($ELR = 311$), which is one of the main areas in China, over which *S. alterniflora* is currently distributed (Liu et al., 2013). Thus, this comparison confirmed the acceptable to superior sustainability of the 7-step EES and its seven subsystems at different temporal and spatial scales, in addition to their high economic viability.

Previous studies showed that by 2014 *S. alterniflora* had expanded to cover 55,468 ha of the coastal area of China (Zhang, 2017), with 92% of the total located in the following provinces: Jiangsu (21843 ha, 39%), Zhejiang (9648 ha, 17%), Shanghai (9548 ha, 17%), and Fujian (9539 ha, 17%, Fig. 2 b). If all the *S. alterniflora* in these 4 areas could be utilized by the 7-step EES described in this study, an economic output of $5.36E+11$ yuan in

Table 5
Ecological economic comparison between the *S. alterniflora* ecological engineering system and other ecological economic systems of the beach/estuary area.

	EYR	ELR	ELR*	ELR _{LS}	ELR _w	ESI	ESI _{LS}	ESI _w	EER	EISD	EISD _{LS}	EISD _w	EBD, yuan/ha/yr.	O/I ratio
<i>S. alterniflora</i> ecological engineering system	1.008	132.93	7.730	0.019	132.93	0.008	52.36	0.008	29.58	0.224	1.55E+03	0.224	2.45E+07	29.58
<i>S. alterniflora</i> harvest subsystem	139.18	0.924	0.007	0.004	0.007	1.92E+04	3.24E+04	1.92E+04	7.600	1.46E+05	2.46E+05	1.46E+05	2.17E+03	7.600
Aquaculture ^a														
Eel	1.043	23.429	22.825	8.735	23.429	0.045	0.119	0.045	2.601	0.116	0.311	0.116	6.71E+05	2.601
Opheichthylus	1.050	20.194	20.119	12.038	20.194	0.052	0.087	0.052	2.697	0.140	0.235	0.140	4.57E+05	2.697
Weever	1.038	26.185	26.089	15.723	26.185	0.040	0.066	0.040	2.998	0.119	0.198	0.119	4.90E+05	2.998
Tourist ^b														
Luhua lake	1.072	13.924	7.306	0.855	13.924	0.077	1.253	0.077	2.623	0.202	3.286	0.202	4.22E+04	2.623
Farmyard	1.011	91.739	30.328	9.213	91.739	0.011	0.110	0.011	3.600	0.040	0.395	0.040	5.61E+05	3.600
Orchard ^c														
Banana	1.040	25.185	10.014	2.382	25.185	0.041	0.436	0.041	2.521	0.104	1.101	0.104	6.02E+04	2.521
Papaya	1.158	40.13	4.061	1.554	4.770	0.029	0.745	0.029	1.816	0.052	1.352	0.441	6.06E+04	1.816
Guava	1.310	43.224	3.239	2.731	3.427	0.030	0.480	0.382	1.975	0.060	0.947	0.755	6.44E+04	1.975
Wampee	1.032	30.894	6.596	2.114	7.491	0.033	0.488	0.138	2.934	0.098	1.433	0.404	1.31E+05	2.934
Lotus	1.042	23.825	2.313	0.991	2.394	0.044	1.052	0.435	2.558	0.112	2.690	1.114	1.14E+05	2.558
Lotus-shrimp	1.039	25.528	2.876	0.999	3.016	0.041	1.040	0.345	2.696	0.110	2.804	0.929	2.63E+05	2.696
Lotus-fish	1.045	22.116	2.384	1.177	2.509	0.047	0.888	0.417	4.954	0.234	4.398	2.063	6.02E+04	4.954

^a Li et al. (2011) (Recalculated based on published raw data).

^b Wang et al. (2008b) (Recalculated based on published raw data).

^c Lu et al. (2009) (Recalculated based on published raw data).

^d Lu et al. (2017) (Recalculated based on published raw data).

Jiangsu, 2.37E+11 yuan in Zhejiang, 2.34E+11 yuan in Shanghai, and 2.34E+11 yuan in Fujian might be realized; which is, respectively, 8%, 6%, 10%, and 10% of the 2014 GDP of the three provinces and one city mentioned above. Considering the high economic O/I ratio (29.58) of the 7-step EES, the broad adoption of this system could have a positive effect on the economy of these four regions. If all 55,468 ha of *S. alterniflora* present in China in 2014 are utilized by this ecological engineering system, it could result in an economic output of 1.41E+12 yuan/yr for the nation, would be over 2% of the national GDP in 2014. This value does not count the marginal ecological-economic benefits gained from invasion control, and the ecological benefits of having the *Spartina* salt marsh on the mudflat in the growing season, e.g. for carbon sequestration, land building, and bank protection etc. (Qin et al., 2019).

Optimization is possible for every system, including the 7-step EES under study here. This system has been developed and optimized, step-by-step, over the past two decades through directed research (Qin et al., 1997, 1998; Zhang et al., 2000a, b; Liu et al., 2004). The sensitivity analysis disclosed that at the subsystem level, encapsulation was the most sensitive subsystem to both the emergy and economic characteristics of the 7-step EES. Simply deleting the encapsulation subsystem can bring over an 85% decrease in the overall environmental loading (ELR), but the load on the local system (ELR_{LS}) was increased 6.1 times. Deleting the encapsulation subsystem, respectively, caused a 599% and 278% increase in long-term and short-term sustainability of the 7-step EES as indicated by ESI and EISD, accompanied by an 85% and 92% decrease in the long-term and short-term sustainability at the local scale, as indicated by ESI_{LS} and EISD_{LS}, respectively. However, the sensitivity analysis of the flows showed that halving the purchased capsule cell input caused a 42% decrease in local long-term sustainability of the 7-step EES, but a 71% increase in EER, a 9% increase in EISD_L, and a 73% and a 228% increase in ESI and EISD (Fig. 4, and Appendix Table C). Also, halving the input of capsule cells resulted in an 89% increase in the economic O/I ratio (Fig. 5, and Appendix Table D). In contrast, doubling the purchased capsule cell input caused an 84% increase in the long-term sustainability of the 7-step EES at the whole system scale, but a decrease in the sustainability at all other temporal-spatial scales, and a 49% decrease in the economic O/I ratio. Thus, decreasing the cost of the purchased capsule cell inputs is a key factor in the optimization of this system that is worth considering to increase both the emergy and economic sustainability and viability at multiple scales.

Furthermore, based on our results combined with the results of previous studies, it is suggested that the harvest of *S. alterniflora* be carried out in the winter (from late October to December) after the typhoon season, which goes from May to September in China, so that the ecosystem disturbance caused by harvesting will not affect the function of the salt marsh in bank protection, which is an essential function of the salt marshes in some areas, e.g. at Longjiang Dam in Zhejiang Province (Min et al., 1997). Another advantage of harvesting *S. alterniflora* during this period is that the water content in the aboveground biomass is low and the content of nutrients and bioactive materials is not significantly lower than when it is at its peak in October (Qin et al., 1997).

Sustainability is an ecological economic concept with multiple temporal and spatial characteristics, and so its evaluation demands that these aspects of the problem be considered. All economic activities are affected by trades with market prices floating around, but generally not equal to the donor (emergy) value of the goods and services. The Emergy Sustainability Index (ESI) is defined as the ratio of EYR to ELR, and is considered to be a measure of the long-term sustainability of the system but it does not consider the impact of trading for inputs and outputs on the market. In the long-term, ESI will give a valid assessment of sustainability, but it

neglects the short-term effects of markets and prices for emergy, which strategy-makers need to understand to make decisions in the short-term and for whom actions are mainly driven by economic benefits. Short-term sustainability, as indicated by the EISD values of the 7-step EES and all seven of its subsystems were higher than their corresponding long-term sustainability values, i.e., ESIs, because all of their EERs were above 1.

On the scale of the whole system, the ELR_{WSS} , ESI_{WSS} and $EISD_{WSS}$ of the 7-step EES and the harvesting and encapsulation subsystems were equal to their ELRs, ESIs, and EISDs, with the biomass of *S. alterniflora* being taken as W_R , and without W_N and F_W inputs (Table 2). The ESI_{WSS} and $EISD_{WSS}$ of the other five subsystems were 2–9 orders of magnitude higher than their ESIs and EISDs, due to the input of the biomass or residues of *S. alterniflora* as F_W , which decreased the environmental loads on the background systems where they were produced.

At the local scale, the ELR_{LS} of the complex 7-step EES and all seven of its subsystems were less than their ELRs, because of the input of F_C and W which increased local processing capacity or decreased local environmental loads. Consequently, the sustainability of the 7-step EES and all seven of its subsystems at the local scale (indicated by ESI_{LS} and $EISD_{LS}$) were higher than their ESIs and EISDs.

Accelerated industrialization and globalization of the world today is accompanied by serious environmental pollution and energy scarcity problems, and as a result, systems become more and more dependent on purchased inputs to optimize the utilization of resources and to treat the negative effects of wastes. Consequently, the multi-spatial scale nature of the ecological and economic characteristics of all systems and processes are attracting more attention (Arce et al., 2016; Duan and Chen, 2017).

The multi-scale emergy index system explored in this study can address this demand by quantitatively clarifying the integrated economic viability, environmental loading and sustainability of the systems and processes under study at different temporal and spatial scales. This method can be applied to integrate ecological and economic evaluations of many systems at different scales and it is not limited to ecological engineering systems.

5. Conclusion

The development of a 7-step EES for the complete utilization of *S. alterniflora* biomass opens the way to convert the human perception of *S. alterniflora* from that of an invasive, nuisance species to that of a valuable resource that can be used as a feedstock to make a health supplement, and then as a medium for cultivation and rearing of valuable products, and finally, as the main component of a microbe-enhanced fertilizer that is returned to the land. The proposed ecological engineering system is zero waste with respect to the harvested grass and appears to be sustainable, not only on both long-term and short-term temporal scales, but also at the local and whole system spatial scales. All subsystems of the complex ecological engineering system had a positive economic benefit, which gives all subsystem owners a reason for further development and perfection of their systems. If the 7-step EES was fully implemented, the economic output could be significant for all four main areas of China's coast where *S. alterniflora* is distributed. This assessment is arrived at without counting the marginal benefit of keeping the expansion of the marsh grass under control, and the ecosystem services provided by *Spartina* saltmarsh, e.g. carbon sequestration, land building, and bank protection etc.

The encapsulation subsystem and, specifically, the input of capsule cells to this subsystem are the most sensitive aspects of the 7-step EES, and the inflow that is most likely to control both the ecological and economic characteristics of the system. Decreasing

the capsule cells purchased or the emergy intensity of this component is the key to optimizing this system for both its sustainability and its ecologic and economic viability on all scales. Further studies are needed to clarify the possibility of getting a low-price capsule cell on the market, and the feasibility of setting up their own capsule cell production line.

Both waste processing and pollution control (including invasive species as a kind of pollutant in the broad sense) are essential characteristics that need to be considered in attaining cleaner production solutions to the complex problems presented by invasive species that have both positive and negative effects on ecosystems. The sustainability of ecological engineering solutions depends on integrated emergy and economic evaluation that can quantitatively clarify the sustainability and viability of ecological economic systems at different temporal and spatial scales. This is essential knowledge for successful environmental planning and strategy-making to move toward cleaner production solutions to the messy problems presented by invasive species, which have complex positive and negative effects on ecosystems. In this study we did not evaluate emissions from the process, thus our study should be extended in the future to more fully capture the overall impacts of the process and to obtain a complete assessment of the overall “cleanness” of the 7-step EES *Spartina* utilization process.

Contribution of authors

Dr. Hongfang Lu and Dr. Daniel E. Campbell contributed in data analyzing, integrated emergy and economic evaluating, manuscript writing and revising.

Dr. Huanshi Zhang, Dr. Pei Qin, and Dr. Xiuzhen Li contributed in data collecting, and manuscript writing and revising.

Declaration of interest statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other person interest of any nature of kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled “Integrated emergy and economic evaluation of an ecological engineering system for the utilization of *Spartina alterniflora*” which was submitted to publication as a research paper in *Journal of Cleaner Production*.

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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.2019.119592>.

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