ENGINEERING Agriculture: https://journal.hep.com.cn/fase
Yiming LI et al., 2027, 14(3): 27733 https://doi.org/10.15302/J-FASE-2027733
RESEARCH ARTICLE

An integrated framework of emergy analysis and LMDI for assessing sustainability: a case study of tobacco production system

Yiming LI[1], Lan YAO[1], Jing LONG[1], Chenchen CHEN[2], Hang YANG[2], Zhengxiong ZHAO[3], Tianshu CHU(✉)[1, 4], Chaochun ZHANG(✉)[1]

1 State Key Laboratory of Nutrient Use and Management; Key Laboratory of Plant-Soil Interactions (Ministry of Education); College of Resources and Environmental Sciences; National Academy of Agriculture Green Development, China Agricultural University, Beijing 100193, China.

2 College of Engineering, China Agricultural University, Beijing 100083, China.

3 College of Resources and Environment, Yunnan Agricultural University, Kunming 650201, China.

4 State Environmental Protection Key Laboratory of Soil Environmental Management and Pollution Control (Ministry of Ecology and Environment), Nanjing Institute of Environmental Sciences, Nanjing 210042, China.

Received November 19, 2025;
Accepted June 16, 2026.
Correspondence: zhangcc@cau.edu.cn

SUPPLEMENTARY MATERIALS

Table S1 Emergy fluxes and related unit emergy values

No.	Item	Emergy value	Reference
Local renewable resources（R）			
1	Sunlight	1 $sej·J^{-1}$	[1]
2	Wind, kinetic energy	800 $sej·J^{-1}$	[2]
3	Rain, geopotential	13,332 $sej·J^{-1}$	[1]
4	Rain, chemical potential	7000 $sej·J^{-1}$	[2]
Local non-renewable resources（N）			
5	Net loss of topsoil	$5.59×10^{4}$ $sej·J^{-1}$	[3]
6	Water	10^{8} $sej·kg^{-1}$	[1]
Purchased renewable resources (FR)			
7	Human labor (10%)	$4.83×10^{5}$ $sej·J^{-1}$	[4]
8	Manure	$1.44×10^{11}$ $sej·kg^{-1}$	[5]
Purchased non-renewable resources (FN)			
9	N	$5.33×10^{12}$ $sej·kg^{-1}$	[1]
10	P_2O_5	$5.84×10^{11}$ $sej·kg^{-1}$	[1]
11	K_2O	$1.21×10^{12}$ $sej·kg^{-1}$	[1]
12	Pesticides	$1.12×10^{13}$ $sej·kg^{-1}$	[3]
13	Plastic film	$4.83×10^{11}$ $sej·kg^{-1}$	[1]
14	Diesel	$6.74×10^{5}$ $sej·J^{-1}$	[1]
15	Electricity	$2.02×10^{5}$ $sej·J^{-1}$	[1]
16	Coal	$5.06×10^{4}$ $sej·J^{-1}$	[1]
17	Human labor (90%)	$4.83×10^{5}$ $sej·J^{-1}$	[4]
Major output			
18	Tobacco	16.42 $MJ·kg^{-1}$	[6]

Note: Local renewable resources include sunlight, wind kinetic energy, rain geopotential energy, and rain chemical potential energy. Following emergy accounting principles[1], these independent driving energy flows were not summed; instead, the maximum local renewable resources (R) was adopted to represent the renewable input and avoid double counting.

Table S2 Comparison between tobacco production and other production systems in China and other countries

Crop type	Country	EYR	EIR	ELR	ESR	%R	ESI	Reference
Cucumber	China	1.13	8.64	18.42	11.0%	30.0%	0.080	[7]
Cucumber	China	1.03	32.61	1319.71	3.0%	27.0%	0.001	[7]
Cucumber	Iran	1.03	40.53	3.98	2.4%	20.1%	0.258	[8]
Cucumber	Iran	1.02	45.11	5.79	2.4%	14.7%	0.176	[8]
Tomato	Iran	1.02	65.36	4.15	1.5%	19.4%	0.245	[8]
Tomato	Iran	1.01	72.90	6.16	1.5%	14.0%	0.164	[8]
Bell paper	Iran	1.01	69.35	4.24	1.4%	19.1%	0.239	[8]
Bell paper	Iran	1.01	77.37	6.01	1.4%	14.3%	0.169	[8]
Eggplant	Iran	1.01	83.43	4.60	1.2%	17.9%	0.220	[8]
Eggplant	Iran	1.01	89.00	6.91	1.2%	12.6%	0.146	[8]
Wheat	China	-	7.18	68.61	13.0%	12.0%	0.030	[9]
Wheat	China	-	6.97	29.84	15.0%	13.0%	0.050	[9]
Wheat	China	-	4.15	10.74	20.0%	17.0%	0.120	[9]
Wheat	China	1.01	-	32.83	-	-	0.031	[10]
Wheat	China	1.01	-	39.17	-	-	0.026	[10]
Wheat	China	1.01	-	45.52	-	-	0.022	[10]
Wheat	China	1.01	-	51.86	-	-	0.020	[10]
Wheat	China	1.02	-	33.66	-	-	0.031	[10]

Wheat	China	1.02	-	39.17	-	-	0.026	[10]
Wheat	China	1.02	-	44.83	-	-	0.023	[10]
Wheat	China	1.01	-	50.21	-	-	0.020	[10]
Wheat	Iran	2.03	65.30	20.69	1.5%	4.6%	0.026	[11]
Rice	China	1.26	-	17.61	-	5.4%	0.071	[12]
Rice	China	1.15	-	25.45	-	3.8%	0.045	[12]
Rice	China	1.15	-	25.32	-	3.8%	0.046	[12]
Rice	China	1.16	-	24.95	-	3.9%	0.046	[12]
Rice	Iran	5.13	0.24	11.11	732.0%	-	0.460	[13]
Rice	Iran	1.55	1.83	83.90	-	20.4%	0.018	[14]
Rice	Iran	1.50	1.99	46.43	-	21.3%	0.032	[14]
Rice	Iran	1.60	1.66	40.90	-	23.0%	0.039	[14]
Maize	Iran	1.01	94.83	24.04	1.0%	4.0%	0.009	[11]
Potato	Iran	1.44	2.29	3.38	-	22.9%	0.570	[15]
Bean	Iran	1.28	-	0.86	-	53.7%	1.480	[16]
Bean	Iran	1.17	-	6.47	-	13.4%	0.180	[16]
Bean	Iran	1.28	-	11.47	-	8.0%	0.110	[16]
Bean	Iran	1.20	-	20.00	-	4.8%	0.060	[16]
Bean	Iran	1.17	-	28.81	-	3.4%	0.040	[16]
Coffee	Colombia	1.34	2.98	5.90	-	-	0.220	[17]
Coffee	Colombia	1.36	2.77	5.80	-	-	0.230	[17]
Coffee	Colombia	1.37	2.71	5.75	-	-	0.240	[17]
Tea	China	1.04	26.78	12.70	3.6%	7.3%	0.082	[18]
Tea	China	1.02	49.00	7.77	2.0%	11.4%	0.131	[18]
Red orange	Italy	1.50	-	43.00	-	-	0.030	[19]
Red orange	Italy	2.60	-	30.00	-	-	0.080	[19]
Red orange	Italy	11.70	-	3.80	-	-	3.100	[19]
Red orange	Italy	1.60	-	24.00	-	-	0.070	[19]
Orange	China	1.03	-	9.59	-	9.4%	0.110	[20]
Orange	China	1.02	-	10.03	-	9.1%	0.100	[20]
Kiwifrui	Italy	1.07	-	10.09	-	9.0%	0.110	[21]
Kiwifrui	Iran	1.08	-	7.26	-	12.1%	0.150	[21]
Kiwifrui	China	1.04	-	10.48	-	8.7%	0.100	[21]
Kiwifrui	China	1.10	-	13.65	-	6.8%	0.080	[21]
Chinese agriculture	China	1.04	-	2.12	-	-	0.520	[22]
Chinese agriculture	China	1.69	6.22	1.33	-	-	1.270	[23]
Chinese agriculture	China	1.68	7.77	2.10	-	-	0.800	[23]

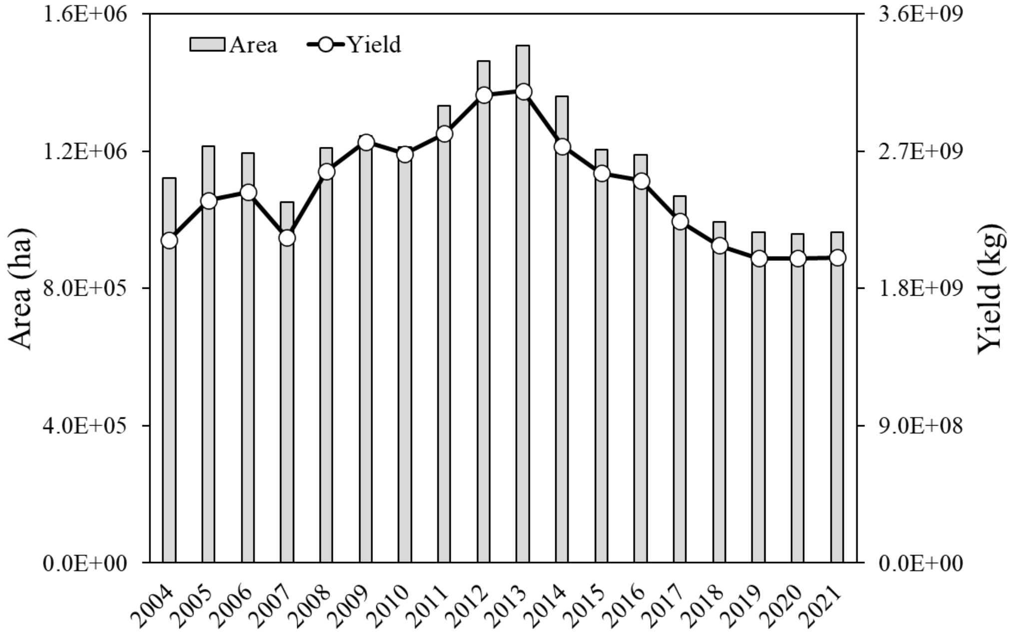

Fig. S1 Temporal changes in planting area and production of flue-cured tobacco in China from 2004 to 2021.

REFERENCES

1. Odum H T. Environmental Accounting: Emergy and Environmental Decision Making. New York: *Wiley*, 1996
2. Brown M T, Ulgiati S. Emergy assessment of global renewable sources. *Ecological Modelling*, 2016, **339**: 148–156
3. Brown M T, Bardi E. Handbook of emergy evaluation. Gainesville: *Center for Environmental Policy*, 2001
4. Lan S, Odum H T, Liu X. Energy flow and emergy analysis of the agro ecosystems of China. *Ecology Science*, 1998, **17**(1): 32–39 (in Chinese)
5. Castellini C, Bastianoni S, Granai C, Bosco A D, Brunetti M. Sustainability of poultry production using the emergy approach: comparison of conventional and organic rearing systems. *Agriculture, Ecosystems & Environment*, 2006, **114**(2–4): 343–350
6. Chu T S, Song Y T, Yang Z L. Sustainability evaluation of crop-livestock production systems in Heilongjiang reclamation area. *Chinese Journal of Agricultural Resources and Regional Planning*, 2022, **43**(3): 8–18 (in Chinese)
7. Zhao H, Zhai X J, Guo L Z, Yang Y J, Li J H, Ren C, Wang K L, Liu X Q, Zhan R Y, Wang K. Comparing protected cucumber and field cucumber production systems in China based on emergy analysis. *Journal of Cleaner Production*, 2019, **236**: 117648
8. Asgharipour M R, Amiri Z, Campbell D E. Evaluation of the sustainability of four greenhouse vegetable production ecosystems based on an analysis of emergy and social characteristics". *Ecological Modelling*, 2020, **424**: 109021
9. Zhao H, Zhai X J, Guo L Z, Liu K S, Huang D, Yang Y J, Li J H, Xie S, Zhang C, Tang S M, Wang K. Assessing the efficiency and sustainability of wheat production systems in different climate zones in China using emergy analysis. *Journal of Cleaner Production*, 2019, **235**: 724–732
10. Xiong L, Shah F, Zhao Y J, Li Z J, Zha X R, Ye M, Wu W. Sustainability analysis of irrigated and rainfed wheat production systems under varying levels of nitrogen fertilizer through coupling of emergy accounting and life cycle assessment. *Journal of Cleaner Production*, 2024, **447**: 141423

11. Zadehdabagh N, Monavari S M, Kargari N, Taghavi L, Pirasteh S. Sustainability of agroecosystems by indices: a comparative study between indicators of ecological footprint sustainability and emergy analysis; a case study in Dez catchment, Iran. *Ecological Modelling*, 2022, **474**: 110165
12. Lyu Y F, Yang X D, Pan H Y, Zhang X H, Cao H X, Ulgiati S, Wu J, Zhang Y Z, Wang G Y, Xiao Y L. Impact of fertilization schemes with different ratios of urea to controlled release nitrogen fertilizer on environmental sustainability, nitrogen use efficiency and economic benefit of rice production: a study case from Southwest China. *Journal of Cleaner Production*, 2021, **293**: 126198
13. Amini S, Rohani A, Aghkhani M H, Abbaspour-Fard M H, Asgharipour M R. Sustainability assessment of rice production systems in Mazandaran Province, Iran with emergy analysis and fuzzy logic. *Sustainable Energy Technologies and Assessments*, 2020, **40**: 100744
14. Eyni-Nargeseh H, Asgharipour M R, Rahimi-Moghaddam S, Gilani A, Damghani A M, Azizi K. Which rice farming system is more environmentally friendly in Khuzestan province, Iran? A study based on emergy analysis. *Ecological Modelling*, 2023, **481**: 110373
15. Shahhoseini H, Ramroudi M, Kazemi H. Emergy analysis for sustainability assessment of potato agroecosystems (case study: golestan province, Iran). *Environment, Development and Sustainability*, 2023, **25**(7): 6393–6418
16. Asgharipour M R, Shahgholi H, Campbell D E, Khamari I, Ghadiri A. Comparison of the sustainability of bean production systems based on emergy and economic analyses. *Environmental Monitoring and Assessment*, 2019, **191**: 2
17. Méndez Rodríguez C, Salazar Benítez J, Rengifo Rodas C F, Corrales J C, Figueroa Casas A. A multidisciplinary approach integrating emergy analysis and process modeling for agricultural systems sustainable management—coffee farm validation. *Sustainability*, 2022, **14**(14): 8931
18. Xu Q, Yang Y, Hu K L, Chen J, Djomo S N, Yang X, Knudsen M T. Economic, environmental, and emergy analysis of China’s green tea production. *Sustainable Production and Consumption*, 2021, **28**: 269–280
19. La Rosa A D, Siracusa G, Cavallaro R. Emergy evaluation of Sicilian red orange production. A comparison between organic and conventional farming. *Journal of Cleaner Production*, 2008, **16**(17): 1907–1914
20. Hu J Y, Ma X H, Lyu Y F, Zhang X H. An integrated environmental-economic assessment of orange production in China during 2010–2020. *Ecological Modelling*, 2024, **498**: 110885
21. Chen Q W, Ma X H, Hu J Y, Zhang X H. Comparison of comprehensive performance of kiwifruit production in China, Iran, and Italy based on emergy and carbon emissions. *Ecological Modelling*, 2023, **483**: 110439
22. Pan H Y, Zheng X Y, Tian X, Geng Y, Zhang X H, Xiao S J, Gao Z Y, Yang Y X, Liu X C, Li L, Huang C Y, Deng S H, Liu Q. Toward sustainable crop production in China: a co-benefits evaluation. *Journal of Cleaner Production*, 2022, **361**: 132285
23. Zhang X H, Zhang R, Wu J, Zhang Y Z, Lin L L, Deng S H, Li L, Yang G, Yu X Y, Qi H, Peng H. An emergy evaluation of the sustainability of Chinese crop production system during 2000–2010. *Ecological Indicators*, 2016, **60**: 622–633