

Appendix A

$$E_0^C = \max \frac{\sum_{r=1}^s u_r y_{r0}}{\sum_{d=1}^D u_d (z_{d0} - \Delta z_{d0}) + \sum_{t_2 \in T^C} \omega_{t_2} b_{t_20} + \sum_{h=1}^H Q_h x_{h0}}$$

$$s.t. \frac{\sum_{d=1}^D u_d z_{dj}}{\sum_{i=1}^m v_i x_{ij} + \sum_{t_1 \in T^P} \omega_{t_1} b_{t_1j}} \leq 1,$$

$$\frac{\sum_{r=1}^s u_r y_{rj}}{\sum_{d=1}^D u_d (z_{dj} - \Delta z_{dj}) + \sum_{t_2 \in T^C} \omega_{t_2} b_{t_2j} + \sum_{h=1}^H Q_h x_{hj}} \leq 1,$$

$$\frac{\sum_{d=1}^D u_d z_{d0}}{\sum_{i=1}^m v_i x_{i0} + \sum_{t_1 \in T^P} \omega_{t_1} b_{t_10}} = E_0^{P*}$$

$$\omega_{t_1}, \omega_{t_2}, u_r, u_d, v_i, Q_h \geq \varepsilon,$$

$$d=1, \dots, D, r=1, \dots, s,$$

$$i=1, \dots, m, h=1, \dots, H,$$

$$j=1, \dots, n, t_1 \in T^P, t_2 \in T^C. \quad (A.1)$$

$$\text{Let } t = \frac{1}{\sum_{d=1}^D u_d (z_{dj} + \Delta z_{dj}) + \sum_{t_2 \in T^C} \omega_{t_2} b_{t_2j} + \sum_{h=1}^H Q_h x_{hj}}, \text{ and set } \psi_{t_1} = \omega_{t_1}, \psi_{t_2} = \omega_{t_2}, \mu_r = u_r, \mu_d =$$

$u_d, v_i = v_i$ and $Q_h = \eta_h$. Using the *Charnes and Cooper* transformation, model (3) is

equivalent to the following linear program.

$$E_0^C = \max \sum_{r=1}^s \mu_r y_{r0}$$

$$s.t. \sum_{d=1}^D \mu_d z_{dj} - \sum_{t_1 \in T^P} \psi_{t_1} b_{t_1j} - \sum_{i=1}^m v_i x_{ij} \leq 0,$$

$$\sum_{r=1}^s u_r y_{rj} - \sum_{t_2 \in T^C} \psi_{t_2} b_{t_2j} - \sum_{d=1}^D \mu_d (z_{dj} - \Delta z_{dj}) - \sum_{h=1}^H \eta_h x_{hj} \leq 0,$$

$$\sum_{d=1}^D \mu_d (z_{d0} - \Delta z_{d0}) + \sum_{t_2 \in T^C} \psi_{t_2} b_{t_20} + \sum_{h=1}^H \eta_h x_{h0} = 1,$$

$$\sum_{d=1}^D \mu_d z_{d0} - E_0^{\mathbf{p}*} \left(\sum_{t_1 \in T^p} \psi_{t_1} b_{t_1 0} + \sum_{i=1}^m v_i x_{i0} \right) = 0,$$

$$\psi_{t_1}, \psi_{t_2}, \mu_r, \mu_d, v_i, \eta_h \geq \varepsilon,$$

$$d=1, \ldots, D, r=1, \ldots s,$$

$$i=1, \ldots, m, h=1, \ldots, H,$$

$$j=1,\ldots,n, \, t_1\!\in\!T^p, \, t_2\!\in\!T^c. \tag{A.2}$$

Appendix B

Table B.1

Carbon source and coefficient

Source	Coefficient	Reference
Pesticides	$4.9341 \text{ kg} \cdot \text{kg}^{-1}$	Oak Ridge National Laboratory, USA
Fertilizers	$0.8956 \text{ kg} \cdot \text{kg}^{-1}$	Oak Ridge National Laboratory, USA
Agricultural film	$5.18 \text{ kg} \cdot \text{kg}^{-1}$	Institute of Agricultural Resources and Ecology, Nanjing Agricultural University
Tillage	$312.6 \text{ kg} \cdot \text{km}^2$	[1]
Irrigation	$266.48 \text{ kg} \cdot \text{hm}^2$	[2]
Agricultural diesel	$0.5927 \text{ kg} \cdot \text{kg}^{-1}$	Intergovernmental Panel on Climate Change (IPCC) 2013

Table B.2

Provincial average carbon footprints of grain transport for consumption and production

Province	Carbon Intensity of Grain Transport for Consumption ($\text{kgCO}_2\text{e/ton}$)	Carbon Intensity of Grain Transport for Supply ($\text{kgCO}_2\text{e/ton}$)
Beijing	38.01	7.58
Tianjin	33	18.67
Hebei	10.33	4.81
Shanxi	13.66	4.11
Inner Mongolia	8.96	32.7
Liaoning	23.09	28.65
Jilin	10.12	32.09
Heilongjiang	4.91	37.68
Shanghai	53.12	9.14
Jiangsu	24.1	8.97
Zhejiang	37.98	4.66
Anhui	8.58	8.89
Fujian	48.94	6.03
Jiangxi	16.15	7.49
Shandong	12.04	6.41
Henan	3.99	7.27
Hubei	15	6.17
Hunan	16.19	4.29
Guangdong	58.32	8.31
Guangxi	49.42	11.29
Hainan	43.08	2.41
Chongqing	19.4	6.91
Sichuan	26.53	5.45
Guizhou	25.5	3.87
Yunnan	41.26	3.28
Shaanxi	26.69	8.37
Gansu	11.89	9.75
Qinghai	49.26	10.95
Ningxia	17.68	14.11
Xinjiang	9.82	22.27

Table B.3

Classification table of Agricultural products input and output regions.

Agricultural products input region			Agricultural products output region		
Province	Generation	Consumption	Province	Generation	Consumption
Beijing	34.46	678.89	Hebei	3778.07	3660.15
Tianjin	224.65	511.83	Inner Mongolia	3592.95	1463.47
Shanxi	1388.56	1440.71	Jilin	3901.42	1439.11
Liaoning	2366.14	2379.39	Heilongjiang	7565.73	1762.84
Shanghai	96.96	801.10	Jiangsu	3690.49	3450.00
Zhejiang	599.61	2385.91	Anhui	4037.55	3068.36
Fujian	497.67	1933.63	Shandong	5399.68	5093.01
Jiangxi	2185.22	2341.36	Henan	6647.70	4809.64
Hubei	2780.47	2844.08	Gansu	1170.72	1136.27
Hunan	3032.16	3580.81	Ningxia	376.94	294.86
Guangdong	1238.06	4947.55	Xinjiang	1567.04	1253.82
Guangxi	1366.37	2622.55			
Hainan	144.34	463.89			
Chongqing	1081.73	1527.78			
Sichuan	3518.13	4406.68			
Guizhou	1101.18	1735.25			
Yunnan	1880.03	2610.82			
Shaanxi	1239.32	1604.18			
Qinghai	105.53	263.26			
Total	24880.59	39079.67	Total	41728.29	27431.53

Table B.4

Phased efficiency of different regions in 2021.

Agricultural input region					Agricultural output region				
Province	PE	CE	EE	CCR	Province	PE	CE	EE	CCR
Beijing	0.31 1	0.73 7	0.22 9	1.00 0	Hebei	0.80 0	1.00 0	0.80 0	1.00 0
Tianjin	1.00 0	1.00 0	1.00 0	1.00 0	Inner Mongolia	1.00 0	0.38 2	0.38 2	0.30 1
Shanxi	0.84 8	0.70 1	0.59 4	0.70 3	Liaoning	0.94 8	0.92 2	0.87 4	1.00 0
Shanghai	0.80 4	0.59 7	0.48 0	1.00 0	Jilin	1.00 0	0.47 5	0.47 5	0.34 2
Zhejiang	0.34 3	0.37 8	0.13 0	0.42 2	Heilongjiang	1.00 0	0.66 1	0.66 1	0.47 7
Fujian	0.38 2	0.36 6	0.14 0	0.39 9	Jiangsu	0.67 4	1.00 0	0.67 4	1.00 0
Jiangxi	0.73 9	0.59 2	0.43 7	0.64 8	Anhui	0.69 4	0.94 4	0.65 5	1.00 0
Hubei	0.55 8	0.62 2	0.34 7	0.62 9	Shandong	0.92 2	1.00 0	0.92 2	1.00 0
Hunan	0.63 9	0.44 7	0.28 6	0.50 4	Henan	1.00 0	0.52 3	0.52 3	0.60 7
Guangdong	0.49 3	0.68 4	0.33 8	0.79 6	Gansu	0.63 6	0.29 4	0.18 7	0.29 4
Guangxi	0.45 9	0.48 5	0.22 2	0.49 9	Ningxia	1.00 0	0.61 1	0.61 1	0.76 9

Hainan	0.23 3	0.36 3	0.08 5	0.36 2	Xinjiang	0.59 9	0.42 5	0.25 5	0.42 0
Chongqing	0.78 0	0.30 1	0.23 5	0.38 8					
Sichuan	0.80 9	0.84 7	0.68 5	0.98 4					
Guizhou	1.00 0	1.00 0	1.00 0	1.00 0					
Yunnan	0.64 0	0.24 0	0.15 3	0.27 7					
Shanxi	0.86 1	0.34 5	0.29 7	0.39 8					
Qinghai	0.71 6	0.14 8	0.10 6	0.17 6					
Average	0.64 5	0.54 7	0.37 6	0.621	Average	0.85 6	0.68 6	0.58 5	0.684

Table B.5

Changes in grain output in agricultural output regions after agriculture allocation optimization.

Output region	Initial grain output	Optimal grain output	Grain output change
Hebei	3825.09	3806.82	-18.27
Inner Mongolia	3840.30	3478.63	-361.67
Liaoning	2538.74	2524.32	-14.42
Jilin	4039.24	5251.01	1211.77
Heilongjiang	7867.72	10228.04	2360.32
Jiangsu	3746.10	3494.41	-251.69
Anhui	4087.56	3270.05	-817.51
Shandong	5500.75	5161.15	-339.60
Henan	6544.17	5235.34	-1308.83
Gansu	1231.46	1187.71	-43.75
Ningxia	368.44	299.25	-69.19
Xinjiang	1735.78	1388.62	-347.16
Total	45325.35	45325.35	0.00

References

- [1] Bai Y, Deng X, Jiang S, Zhao Z, Miao Y. Relationship between climate change and low-carbon agricultural production: A case study in Hebei Province, China. *Ecological Indicators*. 2019;105:438-47.
- [2] Dong B, Ma X, Zhang Z, Zhang H, Chen R, Song Y, et al. Carbon emissions, the industrial structure and economic growth: Evidence from heterogeneous industries in China. *Environmental Pollution*. 2020;262:114322.