Supplementary Materials

Toward climate-smart irrigation: evaluating the sustainability of negative pressure systems through carbon-nitrogen footprint and cost-benefit analysis

Kechun Wang[1], Peng Chen[2], Zhihui Min[3], Shuaihong Chen[1], Zhaoqiang Zhou[2]

[1]Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas of Ministry of Education, Northwest A&F University, Yangling 712100, Shaanxi, China.

[2]School of Water Conservancy and Civil Engineering, Northeast Agricultural University, Harbin 150030, Heilongjiang, China.

[3]Powerchina Zhongnan Engineering Corporation Limited, Changsha 410014, Hunan, China.

Correspondence to: Dr. Peng Chen, School of Water Conservancy and Civil Engineering, Northeast Agricultural University, No.59 Mucai Street, Xiangfang District, Harbin 150030, Heilongjiang, China. E-mail: chenpeng_isotope@163.com

ORCID: Peng Chen (0000-0003-3630-5685)

Text S1 Calculation of system net ecosystem carbon budget (NECB)

The NECB was calculated according to the following Eq. (1-3):

$$NECB = \sum C_{input} - \sum C_{output} = (Fertilizer\ C + GPP) - (Re + Harvested\ C\ removal) \qquad (1)$$

$$GPP = NPP/0.52 \qquad (2)$$

$$NPP = NPP_{aboveground} + NPP_{root} + NPP_{litter} + NPP_{rhizodeposits} \qquad (3)$$

where GPP is the gross primary production. NPP is the net primary production. $NPP_{aboveground}$ and NPP_{root} are the production of aboveground biomass and underground root biomass (25% of aboveground biomass [1]) and are calculated using dry biomass multiplied by corresponding C content (0.4 kg C kg^{-1}). NPP_{litter} is the production of litter, estimated 3% of the total biomass of vegetables, respectively [2]. $NPP_{rhizodeposits}$ represents the production of, including exudates, root hairs and fine roots sloughed off, and accounts for 7% [3] of the total biomass of vegetable, respectively.

Text S2 The cost of a unit of the Negative Pressure Irrigation

(1) Negative Pressure Irrigation (NPI)

Per hectare area: 100 m × 100 m. Assuming a crop row spacing of 50 cm, 200 irrigation lines are required per hectare, each 100 m long. If the cost of the ceramic pipe (outer diameter: 3 cm, inner diameter: 1.5 cm) is 18.97 CNY m^{-1}, the total investment in ceramic pipes is 379400 CNY ha^{-1}. Pipe density is 3.85 g/cm³, total weight is calculated as:

$$\pi/4 \times (3^2 - 1.5^2) \times 20{,}000 \times 100 \times 3.85 / 1000 = 40800.375\ kg\ ha^{-1}$$

Assuming a lifespan of 15 years, the one growth period (30 days) amortized cost is calculated as:

$$379400 / 15 / 365 / 40800.375 \times 30 = 0.0510\ CNY\ kg^{-1}\ ha^{-1}$$

Assuming a lifespan of 10 years, the one growth period (30 days) amortized cost is calculated as:

$$379400 / 15 / 365 \times 30 = 3118.36\ CNY\ ha^{-1}$$

Assuming a lifespan of 5 years, the one growth period (30 days) amortized cost is calculated as:

$$379400 / 15 / 365 \times 30 = 6236.71\ CNY\ ha^{-1}$$

Additional pipe:

525 m of soft PVC pipes are required at a unit cost of 0.3 CNY m^{-1}, totaling 157.5 CNY ha^{-1}.

If each 200-m roll of 4 mm pipe weighs 5 kg, then total weight = (525 / 200) × 5 = 13.125 kg ha^{-1}

Assuming a service life of 2 years, the one growth period (30 days) amortized cost is:

$$157.5 / 2 / 365 / 13.125 \times 30 = 0.4932 \text{ CNY kg}^{-1} \text{ ha}^{-1}$$

Controller units:

Each control unit manages 40 irrigation lines. Thus, 5 sets are required per hectare. Assuming a unit cost of 308 CNY, the total equipment cost is 1540 CNY ha^{-1}. With a 5-year lifespan (including air pressure sensor, liquid level sensor, vacuum pump, single chip microcomputer and peristaltic pump), the one growth period (30 days) amortized cost is:

$$1540 / 5 / 365 \times 30 = 25.32 \text{ CNY ha}^{-1}$$

(2) Operation and Maintenance

Power consumption: Each power converter operates at 12 W. Assuming 5 sets in use for 24 hours per day:

$$\text{Energy consumption} = 12 \times 24 \times 5 / 1000 = 1.44 \text{ kWh ha}^{-1} \text{ day}^{-1}$$
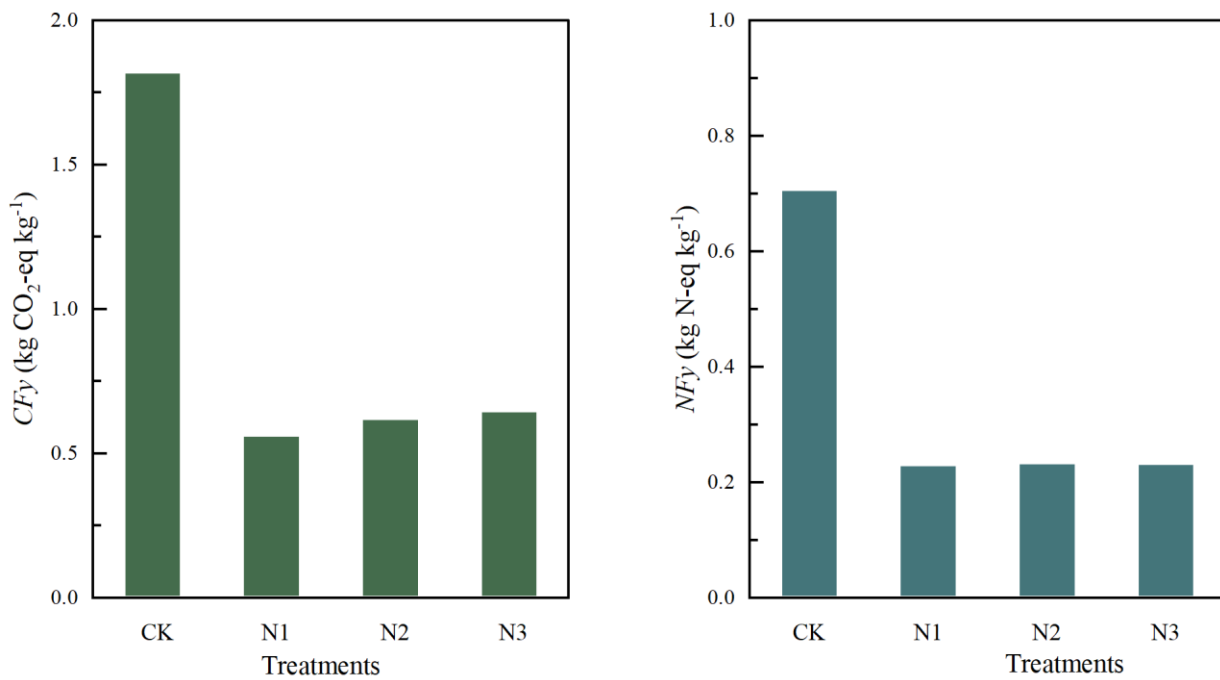

Fig S1. Changes in carbon footprints and nitrogen footprints per unit of yield during the Chinese chives cultivation.

Table S1. Greenhouse gas emissions and reactive nitrogen losses parameters of agricultural products

Item	GHG emissions			Reactive N loss		
	Value	Unit	Reference	Value	Unit	Reference
Labor	0.86	kg CO_2-eq person^{-1} day^{-1}	CLCD0.7	/	/	
N fertilizer	8.39	kg CO2-eq kg^{-1} N	[4]	7.15	kg N_2O-N kg^{-1} N	[4]
Acrylic	6291	kg CO2-eq m^{-3}	climatiq.io	/	/	/
Air pressure sensor	0.0257	Kg CO_2 eq per sensor tag	[5]	/	/	/
Liquid level sensor	0.0257	Kg CO_2 eq per sensor tag	[5]	/	/	/
Vacuum pump	0.223	kg CO_2eq/ usd	climatiq.io	/	/	/
Single chip microcomputer	0.269	kg CO_2eq/ usd	climatiq.io	/	/	/
Peristaltic pump	0.223	kg CO_2eq/ usd	climatiq.io			
PVC water pipe	1.9	kg CO_2e kg^{-1}	climatiq.io			
Ceramic pipe	2.5	kg CO_2e kg^{-1}	Estimated	0.1	kg N_2O-N kg^{-1}	Estimated
Irrigation electricity consumption	0.82	kg CO_2-eq kWh^{-1}	CLCD0.7	0.001	kg NOx-N kWh^{-1}	IKE eBalance v3.0

Note: CLCD0.7 refers to China Life Cycle Database 0.7; Climatiq.io is a platform that integrates greenhouse gas emission factors from multiple internationally recognized sources, providing standardized carbon footprint calculation services.

Table S2. Crop yield and greenhouse gas emissions under different treatments

Items	Unit	Treatments			
		CK	N1	N2	N3
Yield	kg ha^{-1}	2479.38	2441.67	2009.44	1762.22
CO_2 emission	kg CO_2 ha^{-1}	1414.33	347.83	405.07	377.15
N_2O emission	kg N_2O ha^{-1}	1.73	0.38	0.23	0.11

Table S3. Agricultural inputs and unit prices

Item	Unit	Quantity of Input				Unit Price
		CK	N1	N2	N3	
Labor	Person day^{-1}	7.5	0.75	0.75	0.75	106 CNY person^{-1}
N fertilizer	kg N ha^{-1}	208.8	74.86	62.13	53.87	1.8 CNY kg^{-1}
acrylic	m^3 ha^{-1}	0	0.0816	0.0816	0.0816	100 CNY m^{-3}
air pressure sensor	pcs ha^{-1}	0	5	5	5	4 CNY unit^{-1}
liquid level sensor	pcs ha^{-1}	0	5	5	5	15 CNY unit^{-1}
vacuum pump	pcs ha^{-1}	0	5	5	5	60 CNY unit^{-1}
single chip microcomputer	pcs ha^{-1}	0	5	5	5	70 CNY unit^{-1}
peristaltic pump	pcs ha^{-1}	0	5	5	5	59 CNY unit^{-1}
PVC water pipe	kg ha^{-1}	0	13.125	13.125	13.125	0.4932 CNY kg^{-1} ha^{-1}
Ceramic pipe	kg ha^{-1}	0	1435.57	1435.57	1435.57	0.0509 CNY kg^{-1} ha^{-1}
Irrigation electricity consumption	kWh day^{-1} ha^{-1}	0	1.44	1.44	1.44	0.52 CNY kWh^{-1}

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