Supporting information

Supplementary Materials Contents

Part 1: Economic benefits and ecosystem economic benefits 2
Table S1 Main pollutant emissions factors of agricultural inputs in the rice production systems 4
Table S2 Emission factors of N_2O, NH_3 volatilization and N leaching for rice applying with urea and CRU in Central China. 5
Table S3 Mean application rate of various agricultural inputs in 2022-2023 in the rice production system. 6
Table S4 Consumptions of diesel fuel and electricity for agricultural practice in the rice system.... 7
Table S5 Energy equivalents of inputs and outputs in agricultural production system. 8
Table S6 Product price and service price 9
Table S7 Expression and description of resource use, economic and emergy indices 10
Table S8 Emergy analysis under different fertilization modes..... 10
Fig. S1 Characteristics of Shoot height (a), Tiller number (b), SPAD (c) and Leaf Area Index (d)content in different of paddy field models..... 23
Fig. S2 Characteristics of stem, leaf, and panicle dry matter accumulation in different growth stage of paddy field models..... 24
Fig. S3 Characteristics of NH4+-N (a), NO3--N (b), Available P (c) and Available K (d)content in different soil layers of paddy field models..... 25
Fig. S4 Sensitivity to key parameters with N footprint (a),C footprint (b), UEVNmin (c) and EEB (d)..... 26

Part 1: Economic benefits and ecosystem economic benefits

The economic benefits between different N rates or between conventional urea (CU) and the blend of controlled-release urea and conventional urea (BU) resulted from the amount or sale price of fertilizers, along with the labor cost associated with N fertilizer application. Consequently, the N-derived yield benefits (BY), economic benefits (EB), and ecosystem economic benefits (EEB) were calculated.

$BY = (Y - Y_0) \times M_{price}$

$EB = BY - AI_{cost}$

$EEB = BY - AI_{cost} - E_{cost} - H_{cost}$

where BY represents the N-derived yield benefits, Y and Y0 denote the rice grain yield with and without N fertilization, respectively, and M price represents the average local market price of rice from 2022 to 2023, which was 0.36 \$ kg^{-1} . The AI_{cost} refers the costs of agricultural inputs, encompassing the costs of N fertilizer and labor cost for its application (Table S6). E_{cost} represents the costs of ecosystem damage. This includes the impacts of climate warming caused by GHG emission, water eutrophication damage, and soil acidification damage caused by Nr release during the N fertilizer production and application processes. H_{cost} represents the costs to human health that are incurred by the various Nr releases in N fertilizer application. The market prices of fertilizers were 0.34 \$ kg^{-1} for CU and 0.45 \$ kg^{-1} for CRU. The E_{cost} and H_{cost} were calculated by using the following equations, as proposed byYing et al. [39].

$E_{cost} = C_{GHG} + C_{eu} + C_{acid} = (CO_2 \times 0.0204) + (1.12 \times NO_3\text{-}N + 0.24 \times NH_3\text{-}N + 0.0018 \times N) + (1.87 \times NH_3\text{-}N + 0.021 \times N)$ (16)

$H_{cost} = (0.30 \times N_2O\text{–}N_{total} + 0.20 \times NO_3\text{-}N + 3.30 \times NH_3\text{-}N)$ (17)

where C_{GHG} , C_{eu} , and C_{acid} represent the costs associated with GHG, water eutrophication, and soil acidification damages, respectively, as reported by Xia and Yan[40]. The market price of CO_2 was set at 0.0204 \$ kg^{-1} according to the finding of Li et al.[41]. The cost for NO_3-N and NH_3-N to restore the eutrophication impact was set at 1.12 and 0.24 \$ kg^{-1}, respectively [42]; and the cost for NH_3-N to restore the soil acidification damage caused during the N fertilizer application process was set at 1.87 \$ kg^{-1} according to the founding of Xiang et al.[42] and Xia and Yan[41]. The costs for reduction of GHG emission, and restoration of eutrophication and soil acidification damage per kg N fertilizer production were set at 0.20, 0.0018, and 0.021 \$ kg^{-1}, respectively [43]. The costs to human health per

unit of N_2O-N_{total} , NO_3 –N, and NH_3 –N were set at 0.30, 0.20, and 3.30 \$ kg^{-1}, respectively, based on the research of Gu et al.[44]

Part 2:

Table S1 Main pollutant emissions factors of agricultural inputs in the rice production systems

	Unit	Reactive N emission (10^{-3} kg N $unit^{-1}$)	Global warming (kg C_2O-eq $unit^{-1}$)	References
The production and transportation of common N	kg N	7.15	8.3	[7,8]
The production and transportation of controlled N	kg N	7.15	9.02	[7,8]
The production and transportation of P	kg P_2O_5	0.184	0.79	[7,8]
The production and transportation of controlled P	kg P_2O_5	0.184	1.51	[7,8]
The production and transportation of K	kg K_2O	0.146	0.55	[7,8]
The production and transportation of controlled K	kg K_2O	0.146	1.27	[7,8]
Pesticides	kg	4.69	19.13	[7,8]
Electricity for irrigation	kWh	1.97	0.95	[9]
Diesel fuel	L	2.86	3.75	[10]

Note: Compared with common N (PK), the production and transportation of controlled N (PK) mainly increased the electricity and diesel fuel consumption, resulting in 0.72 kg CO_2-eq more GHG emission for 1 kg controlled N (PK); while the reactive N losses difference between common N (PK) and controlled N (PK) could be negligible during production and transportation (there is almost no loss of reactive nitrogen) [7].

Table S2 Emission factors of N_2O, NH_3 volatilization and N leaching for rice applying with urea and CRU in Central China.

Item	N source		References
	Urea	CRU	
N_2O emission (%)	0.92(0.81)	0.27(0.14)	[26,50-52]
NH_3 volatilization (%)	19.61(8.38)	5.58(3.56)	[34,51,57]
N leaching (%)	11.65(3.34)	1.06(0.56)	[26]

Table S3 Mean application rate of various agricultural inputs in 2022-2023 in the rice production system.

Treatment	Urea	CRU	Superphosphate (kg ha^{-1})	Potassium chloride (kg ha^{-1})	Pesticides (kg ha^{-1})	Diesel fuel (L ha^{-1})	Electricity for irrigation (kWh ha^{-1})	Seed (kg ha^{-1})	Labor (h ha^{-1})
CK	0	0	875	175	4.55	70	500	30	119
FFP	270	0							162
CRN	0	220							133
CRNPK	0	220							133
80%CRNPK	0	180							133

*value was the electricity used for irrigation, which was calculated by the irrigation electricity use quantity (100 kWh ha^{-1} per irrigation in Jingzhou city) multiplied by average irrigation time (5 times) across the two growing seasons.

Table S4 Consumptions of diesel fuel and electricity for agricultural practice in the rice system.

Agricultural practice *	Supply (unit)	Consumption rate	Efficiency
Tilling	Diesel fuel (L)	13.1 L h^{-1}	0.80 ha h^{-1}
Fertilizing	Diesel fuel (L)	3.6 L h^{-1}	2.0 ha h^{-1}
Planting for rice seedling	Diesel fuel (L)	4.0 L h^{-1}	0.4 ha h^{-1}
Harvesting	Diesel fuel (L)	15.8 L h^{-1}	2000 kg h^{-1}
Irrigation for rice season	Electricity (kWh)	500 kWh ha^{-1}	25 m^3 kWh^{-1}

* The efficiencies for tilling, fertilizing, and planting or seeding refer to the completed field area per hour, and the efficiency for harvesting refer to the amount of grain harvested per hour; For tilling, fertilizing, and planting or seeding, the diesel fuel consumptions are given by multiplying consumption rate and efficiency; For harvesting, the diesel fuel consumption is given by multiplying consumption rate and the quotient of grain yield and efficiency.

Table S5 Energy equivalents of inputs and outputs in agricultural production system.

Items	Unit	Energy equivalents（MJ unit^{-1})	Direct/Indirect	Renewability
Input				
Labor	h ha^{-1}	1.96	Direct	Renewable
Diesel fuel	L ha^{-1}	56.31	Direct	Non-renewable
Machinery	h ha^{-1}	62.70	Indirect	Non-renewable
Conventional urea (N)	kg ha^{-1}	66.14	Indirect	Non-renewable
Phosphorous (P_2O_5)	kg ha^{-1}	12.44	Indirect	Non-renewable
Potassium (K_2O)	kg ha^{-1}	6.70	Indirect	Non-renewable
CRU (N)	kg ha^{-1}	71.88	Indirect	Non-renewable
Controlled phosphorous (P_2O_5)[a]	kg ha^{-1}	18.18	Indirect	Non-renewable
Controlled potassium (K_2O)[a]	kg ha^{-1}	12.44	Indirect	Non-renewable
Pesticide(active ingredient)	kg ha^{-1}	257.5	Indirect	Non-renewable
Seed (rice)	kg ha^{-1}	14.70	Indirect	Renewable
Electricity	kWh ha^{-1}	12.10	Direct	Non-renewable
Irrigation	m^3 ha^{-1}	1.02	Direct	Renewable
Output				
Rice grain yield	kg ha^{-1}	14.70		
Straw yield	kg ha^{-1}	12.50		

The energy equivalent of CRU was figured out according to the GHG emission rate of control-released urea (CRU) and conventional urea[46].

"a" indicated that compared to common N, CRU-N increased 5.74 MJ kg^{-1} [59], therefore in this research compared to common phosphorous (P) or potassium (K) controlled P or K also increased 5.74 MJ kg^{-1}. And we can estimate the energy equivalents of controlled compound fertilizers based on the controlled N, P and K respectively.

Table S6 Product price and service price

Items	Price
Rice ($ kg-1)	0.36
Urea ($ kg-1)	0.34
CRU ($ kg-1)	0.45
P fertilizer ($ kg-1)	0.16
K fertilizer ($ kg-1)	0.44
Pesticides ($ ha-1)	41.10
Herbicides price($ ha-1)	54.79
Seedling price($ ha-1)	308.22
The price of cultivated land preparation($ ha-1)	164.38
Machine transplanting costs($ ha-1)	82.19
Labor cost for fertilization ($ ha-1)	49.32
Labor cost for using pesticides and herbicides($ ha-1)	49.32
Harvest price($ ha^{-1})	109.59

Table S7 Expression and description of resource use, economic and emergy indices

Index [1)]	Expression [2)]	Description
Single Emergy analysis		
Unit Emergy Value (UEV, sej/J)	UEV=U/Y	The UEV is the ratio of total emergy input to the yield of a system, which is most often measured as joule of available energy (UEV_E).
Renewable fraction (%R)	$R=100\times(L_R+F_R)/U$	The ratio of the renewable emergy invested divided by the total emergy driving the system.
Emergy Yield Ratio (EYR)	EYR=U/F	The ratio of total emergy dividided by the emergy imported from outside the system; it indicates the ability of a process to exploit available local resources by investing outside resources.
Environmental Loading Ratio (ELR)	$ELR=(L_N+F_N)/(L_R+F_R)$	It is a ratio of total nonrenewable emergy (be it local or imported) divided by the total renewable emergy and measured by the loading of the nonrenewable resource use on the locally or globally available ecosystem services.
Emergy Sustainability Index (ESI)	ESI=EYR/ELR	The index is used to evaluate the sustainability of a system (emergy yield versus environmental loading).
UEV based on soil nutrients		
soil mineral N (UEV_{Nmin}, sej/mg/kg)	$UEV_{Nmin}=U/N_{min}$	Evaluates UEV of per unit changeable soil N_{min} at harvest season.
UEV based on GWP		
GWP (UEV_{GWP}, sej/kg CO_2-eq)	UEV_{GWP}= U/GWP	The pressure of GWP from RR system on environment was evaluated.
UEV based on economic indicators		
Benefit ($UEV_{Benefit}$, sej/¥)	$UEV_{Benefit}$=U/Benefit	Evaluates economic benefit of one system
Total revenue ($UEV_{Total\ revenue}$, sej/¥)	$UEV_{Total\ revenue}$=U/Total revenue	Evaluates economic benefit of one system

[1)] UEV, EYR, ELR and ESI is defined inDing et al.[28]

[2)] U: Total emergy inputs; Y: Yield, ie. the product generated by a process. The total emergy input U is the total environmental production cost of the yield; L_R or L_N: Free local renewable or nonrenewable resources; F: Feedback from the economic or purchased resources; F_R or F_N: Renewable or nonrenewable fractions of purchased resources.

[3)] GWP: GWP= $(N_2O\times268)+(CH_4\times30)$

[4)] NH_4^+-N and NO_3^--N (0 ~ 60 cm soil layer): The data is the value of soil NH_4^+-N and NO_3^--N in 0 ~ 60 cm soil layer during ratoon rice harvest.

[5)] N_{min}: N_{min}= 2-year average of NH_4^+-N (0 ~ 60 cm soil layer) ＋NO_3^--N (0 ~ 60 cm soil layer)

Table S8 Emergy analysis under different fertilization modes

No.	Item	Raw data					Unit	RNF[a]	UEV	Emergy (sej)				
		CK	FFP	CRN	CRNPK	80%CRNPK			(sej/unit)	CK	FFP	CRN	CRNPK	80%CRNPK
Free local renewable resources (L_R)														
1	Solar radiation	1.65E+13	1.65E+13	1.65E+13	1.65E+13	1.65E+13	J	1	1.00E+00	1.65E+13	1.65E+13	1.65E+13	1.65E+13	1.65E+13
2	Wind	2.09E+10	2.09E+10	2.09E+10	2.09E+10	2.09E+10	J	1	8.00E+02	1.67E+13	1.67E+13	1.67E+13	1.67E+13	1.67E+13
3	Rain chemical energy	3.22E+10	5.94E+10	5.94E+10	5.94E+10	5.94E+10	J	1	7.00E+03	2.25E+14	4.16E+14	4.16E+14	4.16E+14	4.16E+14
4	River water (Chemical)	3.71E+10	3.71E+10	3.71E+10	3.71E+10	3.71E+10	J	1	6.50E+04	2.41E+15	2.41E+15	2.41E+15	2.41E+15	2.41E+15
Free local nonrenewable resources (L_N)														
5	Net soil loss	3.22E+10	3.22E+10	3.22E+10	3.22E+10	3.22E+10	J	0	9.40E+04	3.03E+15	3.03E+15	3.03E+15	3.03E+15	3.03E+15
Economic imported resources (F)														
6	N fertilizer	0.00E+00	2.70E+06	2.25E+06	1.05E+06	8.40E+05	g	0	6.61E+07	0.00	1.79E+14	1.49E+14	6.94E+13	5.56E+13
7	Compound fertilizer	0.00E+00	0.00E+00	0.00E+00	1.20E+06	9.60E+05	g	0	7.19E+07	0.00	0.00	0.00	8.63E+13	6.90E+13
8	Phosphorous	1.05E+06	1.05E+06	1.05E+06	0.00E+00	0.00E+00	g	0	1.24E+07	1.31E+13	1.31E+13	1.31E+13	0.00E+00	0.00E+00
9	Potassium	1.05E+06	1.05E+06	1.05E+06	0.00E+00	0.00E+00	g	0	6.70E+06	7.04E+12	7.04E+12	7.04E+12	0.00E+00	0.00E+00
10	Pesticides	4.55E+03	4.55E+03	4.55E+03	4.55E+03	4.55E+03	g	0	2.58E+08	1.17E+12	1.17E+12	1.17E+12	1.17E+12	1.17E+12
11	Machine and tools	4.80E+03	6.00E+03	5.93E+03	5.55E+03	5.42E+03	¥	0	8.57E+09	4.11E+13	5.14E+13	5.08E+13	4.75E+13	4.65E+13
12	Electricity	6.25E+09	6.25E+09	6.25E+09	6.25E+09	6.25E+09	J	0.09	1.21E+07	7.56E+16	7.56E+16	7.56E+16	7.56E+16	7.56E+16
13	Diesel	7.00E+04	7.00E+04	7.00E+04	7.00E+04	7.00E+04	g	0	4.09E+04	2.86E+09	2.86E+09	2.86E+09	2.86E+09	2.86E+09
14	Labor	4.01E-02	5.46E-02	5.46E-02	5.46E-02	5.46E-02	year	0.6	4.98E+16	2.00E+15	2.72E+15	2.72E+15	2.72E+15	2.72E+15
15	Services	9.80E+03	1.10E+04	1.08E+04	1.09E+04	1.01E+04	¥	0.05	7.54E+11	7.39E+15	8.29E+15	8.14E+15	8.22E+15	7.62E+15
16	Seeds	4.80E+08	4.80E+08	4.80E+08	4.80E+08	4.80E+08	J	1	1.47E+07	7.06E+15	7.06E+15	7.06E+15	7.06E+15	7.06E+15

17 Straw back to field	1.11E+11	1.27E+11	1.23E+11	1.45E+11	1.37E+11	J	0.37	1.25E+07	1.39E+18	1.58E+18	1.54E+18	1.81E+18	1.71E+18
Yield with L &S (J/ha/yr)													
Rice by CK system	1.29E+11					J		1.15E+07					
Rice by FFP system	1.47E+11					J		1.15E+07					
Rice by CRN system	1.43E+11					J		1.10E+07					
Rice by CRNPK system	1.68E+11					J		1.14E+07					
Rice by 80%CRNPK system	1.59E+11					J		1.13E+07					
Emergy flows (sej)													
Free local renewable resources (L_R)									4.48866E+15	4.48866E+15	4.48866E+15	4.48866E+15	4.48866E+15
Free local nonrenewable resources (L_N)									2.0398E+14	2.0398E+14	2.0398E+14	2.0398E+14	2.0398E+14
Economic imported resources (F)									1.47779E+18	1.67635E+18	1.63272E+18	1.90451E+18	1.80609E+18
Renewable fraction of purchased inputs (F_R)									5.28123E+17	6.01396E+17	5.85314E+17	6.85858E+17	6.49647E+17
Non-renewable fraction of purchased inputs (F_N)									9.49663E+17	1.07495E+18	1.04741E+18	1.21865E+18	1.15644E+18
Renewable emergy flows (L_R+ F_R)									5.32611E+17	6.05885E+17	5.89802E+17	6.90346E+17	6.54136E+17
Non-renewable emergy flows (L_N+ F_N)									9.49867E+17	1.07515E+18	1.04761E+18	1.21885E+18	1.15665E+18
Total emergy input (U) with L&S									1.48248E+18	1.68104E+18	1.63741E+18	1.9092E+18	1.81078E+18

Calculations of CK treatment in ratoon rice mode.

1. Solar energy:

   Land area = 10000 m^2.

   Isolation = 5.14E+09 J/m^2/yr.

   Albedo = 20%.

   Length of cropping cycle = 150 days.

   Energy (J) = 5.14E+09 J/m^2/yr × (1-20%) ×10000 m^2 × 150 day/365 = 1.69E+13 J/ha.

2. Wind energy:

   Land area = 10000 m^2.

   Wind speed = 3 m/s.

   Air density = 1.23 kg/m^3.

   Drag coefficient = 2.00E-03.

   Time (s) = 3.15E+07 s/yr.

   Energy (J) = 10000 m^2 ×1.23 kg/m^3 × 2.00E-03 × $(3)^3$ m/s ×3.15E+7 s = 2.09E+10 J/ha.

3. Rain chemical energy:

   Land area = 10000 m^2.

   Rainfall = 0.651 m/yr.

   Conversion = 1000 kg/m^3.

   Gibbs free energy = 4940 J/kg.

   Energy (J) = 0.651 m/yr × 10000 m^2 ×1000 kg/m^3 ×4940 J/kg = 3.22E+10 J/ha.

4. Irrigation (River water):

   Average quantity = 7500 m^3/ha.

   Conversion = 1000 kg/m^3.

   Gibbs free energy = 4940 J/kg.

   Energy (J) = 7500 m^3/ha × 1000 kg/m^3 ×4940 J/kg = 3.71E+10 J/ha.

5. Soil runoff:

   Average soil loss = 5.25 t/ha. [59]

   Organic matter = 1.83 %. [59]

   Organic matter energy = 5400 kcal/kg.

   Conversion = 4186 J/kcal.

   Energy of net soil loss = 5.25E+03 kg/ha × 0.0183 kg/kg soil × 5400 kcal/kg × 4186 J/kcal = 2.17E+09 J/ha.

6. N fertilizer:

   Land area = 10000 m^2.

   Quantity =0 g/ha.

   The effective content = 46%.

   Average quantity = 10000 m^2 × 0g/ha × 46% = 0 g/ha.

7. Compound fertilizer:

   Land area = 10000 m^2.

   Quantity =0 g/ha.

   Average quantity = 10000 m^2 ×0 g/ha = 0 g/ha.

8. Pestisides:

   Quantity = 4.55E+03 g/ha.

9. Machine and tools:

Total use = 4.80E+03 g/ha.

10. Electricity:

    Consumption =500 kW h/ha

    Conversion = 1.25E+07 J/kW h

    Energy (J) = 500 kW h/ha × 1.25E+07 J/kW h = 3.19E+09 J/ha.

11. Diesel:

    Total use = 7.00E+04 g/ha.

12. Labor:

    Average quantity = 7.22 days/ha (Daily working time is 8 h).

    Working days were 180 in 2018.

    Working years = 7.22 days / 180 days

13. Services:

    Average value = 9.80E+03 ￥/ha.

14. Seeds:

    Quantity = 30 kg/ha.

    Conversion = 1.60E+07 J/kg.

    Energy (J) = 22.88 kg/ha × 1.60E+07 J/kg = 3.66E+08 J/ha.

Yield:

Rice:

Quantity = 12883.3 kg/ha.

Conversion = 1.51E+07 J/kg.

Energy (J) = 12883.3 kg/ha × 1.51E+07 J/kg = 1.95E+11 J/ha.

Calculations of FFP treatment in ratoon rice mode.

15. Solar energy:

    Land area = 10000 m^2.

    Isolation = 5.14E+09 J/m^2/yr.

    Albedo = 20%.

    Length of cropping cycle = 150 days.

    Energy (J) = 5.14E+09 J/m^2/yr × (1-20%) ×10000 m^2 × 150 day/365 = 1.69E+13 J/ha.

16. Wind energy:

    Land area = 10000 m^2.

    Wind speed = 3 m/s.

    Air density = 1.23 kg/m^3.

    Drag coefficient = 2.00E-03.

    Time (s) = 3.15E+07 s/yr.

    Energy (J) = 10000 m^2 ×1.23 kg/m^3 × 2.00E-03 × $(3)^3$ m/s ×3.15E+7 s = 2.09E+10 J/ha.

17. Rain chemical energy:

    Land area = 10000 m^2.

    Rainfall = 0.651 m/yr.

    Conversion = 1000 kg/m^3.

    Gibbs free energy = 4940 J/kg.

    Energy (J) = 0.651 m/yr × 10000 m^2 ×1000 kg/m^3 ×4940 J/kg = 3.22E+10 J/ha.

18. Irrigation (River water):

    Average quantity = 7500 m^3/ha.

    Conversion = 1000 kg/m^3.

    Gibbs free energy = 4940 J/kg.

    Energy (J) = 7500 m^3/ha × 1000 kg/m^3 ×4940 J/kg = 3.71E+10 J/ha.

19. Soil runoff:

    Average soil loss = 5.25 t/ha. [59]

    Organic matter = 1.83 % [59]

    Organic matter energy = 5400 kcal/kg.

    Conversion = 4186 J/kcal.

    Energy of net soil loss = 5.25E+03 kg/ha × 0.0183 kg/kg soil × 5400 kcal/kg × 4186 J/kcal = 2.17E+09 J/ha.

20. N fertilizer:

    Land area = 10000 m^2.

    Quantity = 2.70E+06 g/ha.

    The effective content = 46%.

    Average quantity = 10000 m^2 × 3.00E+05 g/ha × 46% .

21. Compound fertilizer:

    Land area = 10000 m^2.

    Quantity = 0 g/ha.

    Average quantity = 10000 m^2 ×4.20E+05 g/ha

22. Pestisides:

    Quantity = 4.55E+03 g/ha.

23. Machine and tools:

    Total use = 6.00E+03 g/ha.

24. Electricity:

    Consumption =500 kW h/ha

    Conversion = 1.25E+07 J/kW h

    Energy (J) = 500 kW h/ha × 1.25E+07 J/kW h

25. Diesel:

    Total use = 7.00E+04 g/ha.

26. Labor:

    Average quantity = 9.83 days/ha (Daily working time is 8 h).

    Working days were 180 in 2018.

    Working years = 9.83days / 180 days

27. Services:

    Average value = 1.10E+04 ￥/ha.

28. Seeds:

    Quantity = 30 kg/ha.

    Conversion = 1.60E+07 J/kg.

    Energy (J) = 22.88 kg/ha × 1.60E+07 J/kg = 3.66E+08 J/ha.

Yield:

Rice:

Quantity = 8513.552 kg/ha.

Conversion = 1.51E+07 J/kg.

Energy (J) = 8513.552 kg/ha × 1.51E+07 J/kg = 1.51E+07 J/ha.

Calculations of CRN treatment in ratoon rice mode.

29. Solar energy:

    Land area = 10000 m^2.

    Isolation = 5.14E+09 $J/m^2/yr$.

    Albedo = 20%.

    Length of cropping cycle = 150 days.

    Energy (J) = 5.14E+09 $J/m^2/yr$ × (1-20%) ×10000 m^2 × 150 day/365 = 1.69E+13 J/ha.

30. Wind energy:

    Land area = 10000 m^2.

    Wind speed = 3 m/s.

    Air density = 1.23 kg/m^3.

    Drag coefficient = 2.00E-03.

    Time (s) = 3.15E+07 s/yr.

    Energy (J) = 10000 m^2 ×1.23 kg/m^3 × 2.00E-03 × $(3)^3$ m/s ×3.15E+7 s = 2.09E+10 J/ha.

31. Rain chemical energy:

    Land area = 10000 m^2.

    Rainfall = 0.651 m/yr.

    Conversion = 1000 kg/m^3.

    Gibbs free energy = 4940 J/kg.

    Energy (J) = 0.651 m/yr × 10000 m^2 ×1000 kg/m^3 ×4940 J/kg = 3.22E+10 J/ha.

32. Irrigation (River water):

    Average quantity = 7500 m^3/ha.

    Conversion = 1000 kg/m^3.

    Gibbs free energy = 4940 J/kg.

    Energy (J) = 7500 m^3/ha × 1000 kg/m^3 ×4940 J/kg = 3.71E+10 J/ha.

33. Soil runoff:

    Average soil loss = 5.25 t/ha [59]

    Organic matter = 1.83 %. [59]

    Organic matter energy = 5400 kcal/kg.

    Conversion = 4186 J/kcal.

    Energy of net soil loss = 5.25E+03 kg/ha × 0.0183 kg/kg soil × 5400 kcal/kg × 4186 J/kcal = 2.17E+09 J/ha.

34. N fertilizer:

    Land area = 10000 m^2.

    Quantity = 2.25E+065 g/ha.

    The effective content = 46%.

    Average quantity = 10000 m^2 × 2.25E+065g/ha × 46%

35. Compound fertilizer:

    Land area = 10000 m^2.

    Quantity = 0 g/ha.

    Average quantity = 10000 m^2 ×0 g/ha

36. Pestisides:

    Quantity = 4.55E+03 g/ha.

37. Machine and tools:

    Total use = 4.50E+05 g/ha.

38. Electricity:

    Consumption =500 kW h/ha

    Conversion = 1.25E+07 J/kW h

    Energy (J) =500 kW h/ha × 1.25E+07 J/kW h

39. Diesel:

    Total use = 7.00E+04 g/ha.

40. Labor:

    Average quantity = 9.83 days/ha (Daily working time is 8 h).

    Working days were 180 in 2018.

    Working years = 9.83 days / 180 days

41. Services:

    Average value = 1.10E+04 ￥/ha.

42. Seeds:

    Quantity = 30 kg/ha.

    Conversion = 1.60E+07 J/kg.

    Energy (J) = 22.88 kg/ha × 1.60E+07 J/kg = 3.66E+08 J/ha.

Yield:

Rice:

    Quantity = 9662.439 kg/ha.

    Conversion = 1.51E+07 J/kg.

    Energy (J) = 9662.439 kg/ha × 1.51E+07 J/kg = 1.46E+11 J/ha.

Calculations of CRNPK treatment in ratoon rice mode.

43. Solar energy:

    Land area = 10000 m^2.

    Isolation = 5.14E+09 J/m^2/yr.

    Albedo = 20%.

    Length of cropping cycle = 150 days.

    Energy (J) = 5.14E+09 J/m^2/yr × (1-20%) ×10000 m^2 × 150 day/365 = 1.69E+13 J/ha.

44. Wind energy:

    Land area = 10000 m^2.

    Wind speed = 3 m/s.

    Air density = 1.23 kg/m^3.

    Drag coefficient = 2.00E-03.

    Time (s) = 3.15E+07 s/yr.

    Energy (J) = 10000 m^2 ×1.23 kg/m^3 × 2.00E-03 × $(3)^3$ m/s ×3.15E+7 s = 2.09E+10 J/ha.

45. Rain chemical energy:

    Land area = 10000 m^2.

    Rainfall = 0.651 m/yr.

    Conversion = 1000 kg/m^3.

    Gibbs free energy = 4940 J/kg.

    Energy (J) = 0.651 m/yr × 10000 m^2 ×1000 kg/m^3 ×4940 J/kg = 3.22E+10 J/ha.

46. Irrigation (River water):

    Average quantity = 7500 m^3/ha.

    Conversion = 1000 kg/m^3.

    Gibbs free energy = 4940 J/kg.

    Energy (J) = 7500 m^3/ha × 1000 kg/m^3 ×4940 J/kg = 3.71E+10 J/ha.

47. Soil runoff:

    Average soil loss = 5.25 t/ha. [59]

    Organic matter = 1.83 %. [59]

    Organic matter energy = 5400 kcal/kg.

    Conversion = 4186 J/kcal.

    Energy of net soil loss = 5.25E+03 kg/ha × 0.0183 kg/kg soil × 5400 kcal/kg × 4186 J/kcal = 2.17E+09 J/ha.

48. N fertilizer:

    Land area = 10000 m^2.

    Quantity = 1.05E+06 g/ha.

    The effective content = 46%.

    Average quantity = 10000 m^2 × 1.05E+06 g/ha × 46% = 1.29E+05 g/ha.

49. Compound fertilizer:

    Land area = 10000 m^2.

    Quantity = 1.20E+06 g/ha.

    Average quantity = 10000 m^2 ×1.20E+06 g/ha

50. Pestisides:

    Quantity = 4.55E+03 g/ha.

51. Machine and tools:

    Total use = 4.50E+05 g/ha.

52. Electricity:

    Consumption =500 kW h/ha

    Conversion = 1.25E+07 J/kW h

    Energy (J) = 500 kW h/ha × 1.25E+07 J/kW h

53. Diesel:

    Total use = 7.00E+04 g/ha.

54. Labor:

    Average quantity = 9.83 days/ha (Daily working time is 8 h).

    Working days were 180 in 2018.

    Working years = 9.83 days / 180 days

55. Services:

    Average value = 1.10E+04 ￥/ha.

56. Seeds:

    Quantity = 30 kg/ha.

    Conversion = 1.60E+07 J/kg.

    Energy (J) = 22.88 kg/ha × 1.60E+07 J/kg = 3.66E+08 J/ha.

Yield:

Rice:

    Quantity = 9899.868 kg/ha.

    Conversion = 1.51E+07 J/kg.

    Energy (J) = 9899.868 kg/ha × 1.51E+07 J/kg = 1.49E+11 J/ha.

Calculations of 80%CRNPK treatment in ratoon rice mode.

57. Solar energy:

    Land area = 10000 m^2.

    Isolation = 5.14E+09 $J/m^2/yr$.

    Albedo = 20%.

    Length of cropping cycle = 150 days.

    Energy (J) = 5.14E+09 $J/m^2/yr$ × (1-20%) ×10000 m^2 × 150 day/365 = 1.69E+13 J/ha.

58. Wind energy:

    Land area = 10000 m^2.

    Wind speed = 3 m/s.

    Air density = 1.23 kg/m^3.

    Drag coefficient = 2.00E-03.

    Time (s) = 3.15E+07 s/yr.

    Energy (J) = 10000 m^2 ×1.23 kg/m^3 × 2.00E-03 × $(3)^3$ m/s ×3.15E+7 s = 2.09E+10 J/ha.

59. Rain chemical energy:

    Land area = 10000 m^2.

    Rainfall = 0.651 m/yr.

    Conversion = 1000 kg/m^3.

    Gibbs free energy = 4940 J/kg.

    Energy (J) = 0.651 m/yr × 10000 m^2 ×1000 kg/m^3 ×4940 J/kg = 3.22E+10 J/ha.

60. Irrigation (River water):

    Average quantity = 7500 m^3/ha.

    Conversion = 1000 kg/m^3.

    Gibbs free energy = 4940 J/kg.

    Energy (J) = 7500 m^3/ha × 1000 kg/m^3 ×4940 J/kg = 3.71E+10 J/ha.

61. Soil runoff:

    Average soil loss = 5.25 t/ha. [59]

    Organic matter = 1.83 %. [59]

    Organic matter energy = 5400 kcal/kg.

    Conversion = 4186 J/kcal.

    Energy of net soil loss = 5.25E+03 kg/ha × 0.0183 kg/kg soil × 5400 kcal/kg × 4186 J/kcal = 2.17E+09 J/ha.

62. N fertilizer:

    Land area = 10000 m^2.

    Quantity = 8.40E+05 g/ha.

    The effective content = 46%.

    Average quantity = 10000 m^2 × 8.40E+05g/ha × 46%

63. Compound fertilizer:

    Land area = 10000 m^2.

    Quantity = 9.60E+05 g/ha.

    Average quantity = 10000 m^2 ×9.60E+05 g/ha

64. Pestisides:

    Quantity = 4.55E+03 g/ha.

65. Machine and tools:

    Total use = 4.50E+05 g/ha.

66. Electricity:

    Consumption =500 kW h/ha

    Conversion = 1.25E+07 J/kW h

    Energy (J) = 500 kW h/ha × 1.25E+07 J/kW h

67. Diesel:

    Total use = 7.00E+04 g/ha.

68. Labor:

    Average quantity = 9.83 days/ha (Daily working time is 8 h).

    Working days were 180 in 2018.

    Working years = 9.83 days / 180 days

69. Services:

    Average value = 1.10E+04 ￥/ha.

70. Seeds:

    Quantity = 30 kg/ha.

    Conversion = 1.60E+07 J/kg.

    Energy (J) = 22.88 kg/ha × 1.60E+07 J/kg = 3.66E+08 J/ha.

Yield:

Rice:

    Quantity = 11112.48 kg/ha.

    Conversion = 1.51E+07 J/kg.

    Energy (J) = 11112.48 kg/ha × 1.51E+07 J/kg = 1.68E+11 J/ha.

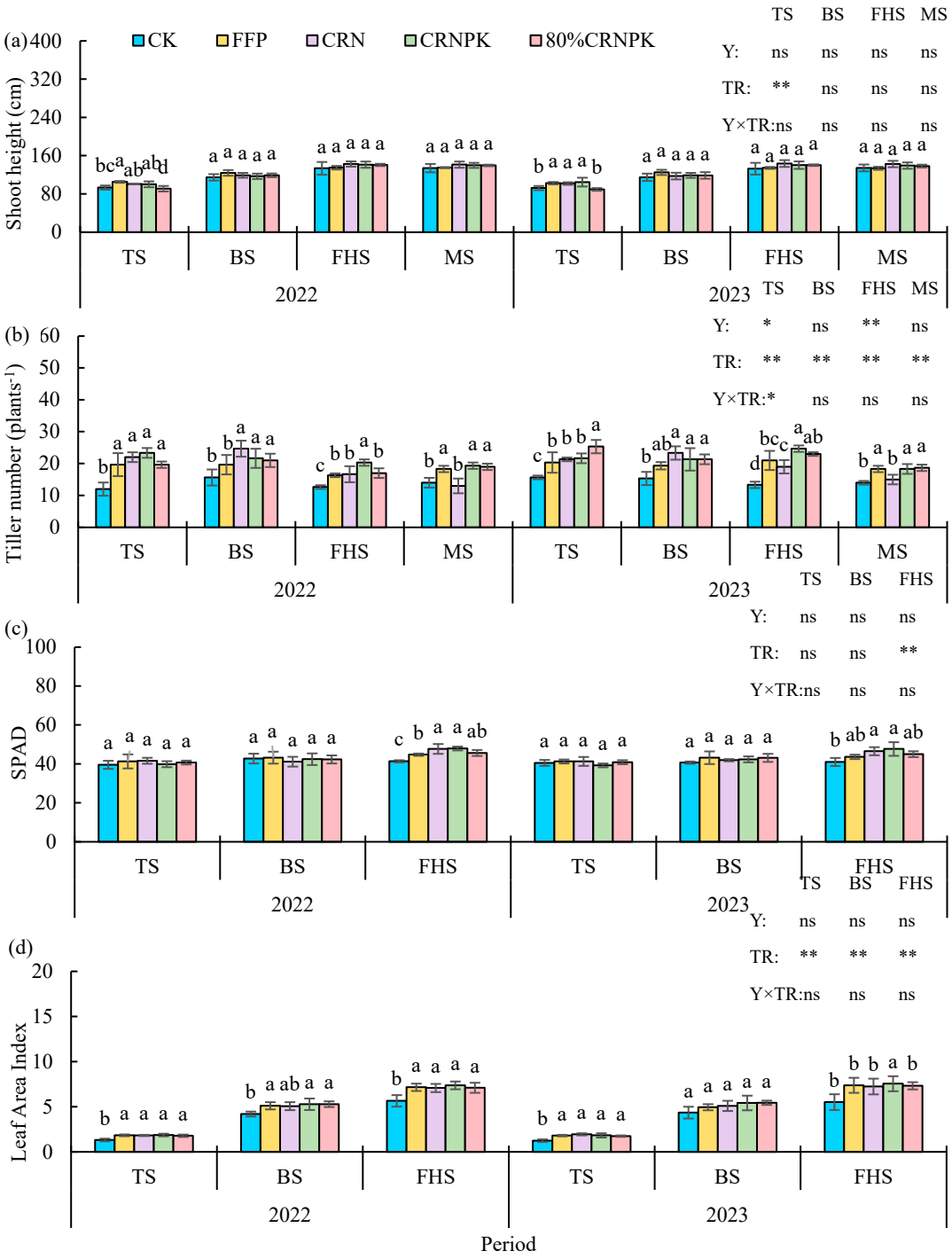


Fig. S1 Characteristics of Shoot height (a), Tiller number (b), SPAD (c) and Leaf Area Index (d)content in different of paddy field models.

Different lowercase letters indicate significant differences among treatments for the same year. Y: year; TR, Treatment. *$P < 0.05$; **$P < 0.01$; ns: non-significance

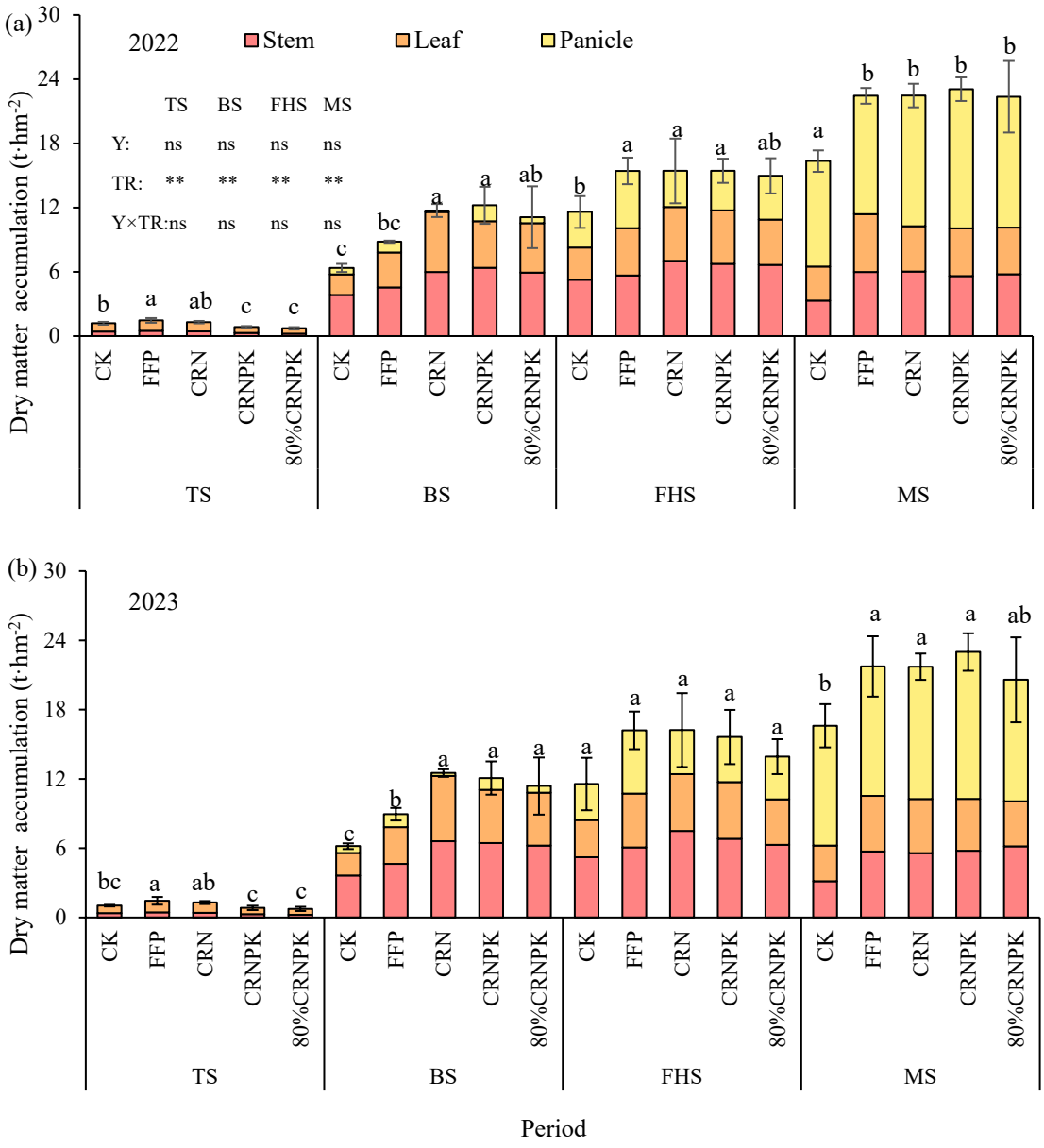


Fig. S2 Characteristics of stem, leaf, and panicle dry matter accumulation in different growth stage of paddy field models.

TS, Tillering stage; BS, Booting stage; FHS, Full heading stage. Different lowercase letters indicate significant difference among treatments for the same year. Y, year; TR, treatments. *P < 0.05; **P < 0.01; ns: non-significance.

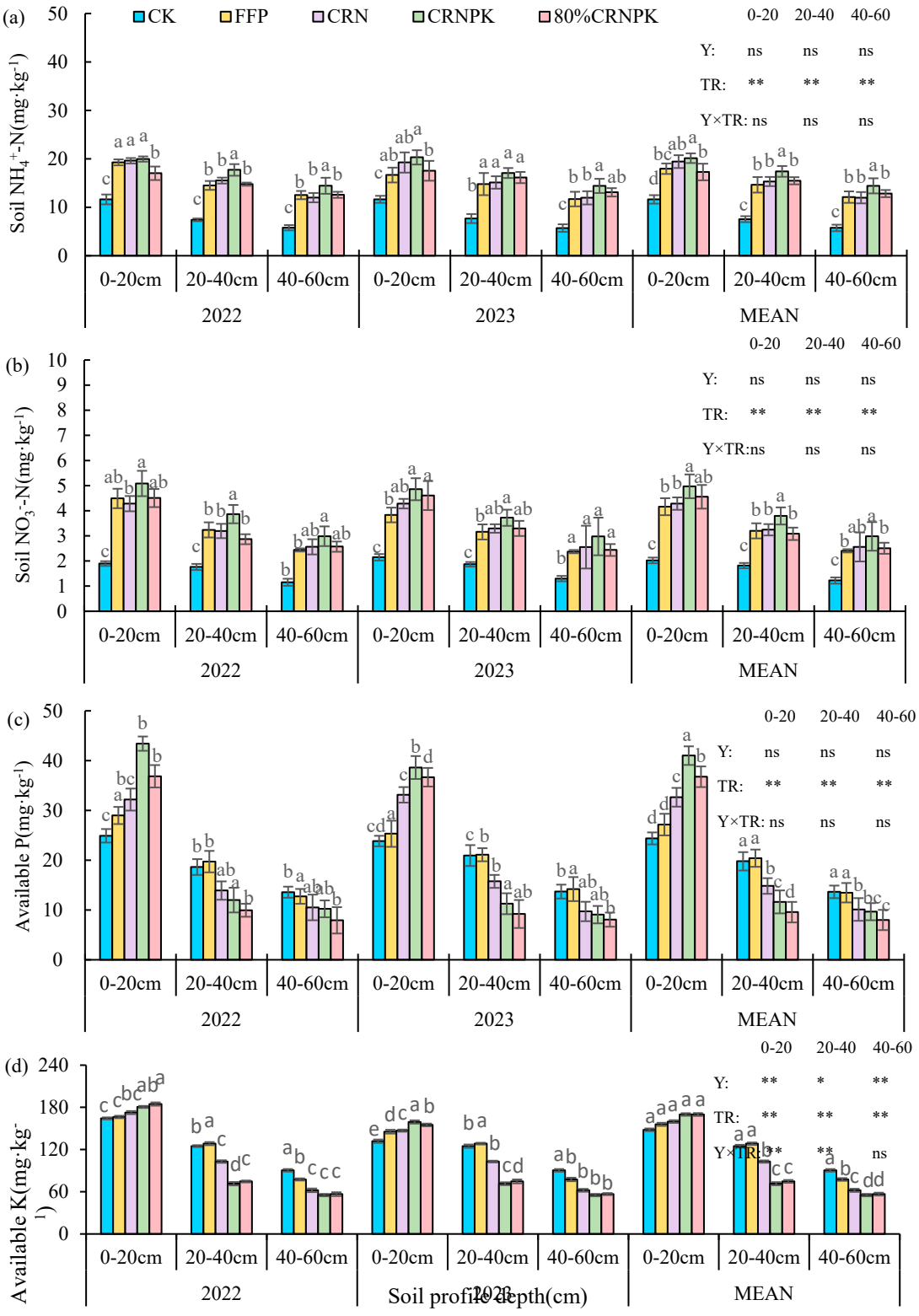


Fig. S3 Characteristics of NH4+-N (a), NO3--N (b), Available P (c) and Available K (d)content in different soil layers of paddy field models.

Different lowercase letters indicate significant differences among treatments for the same year. Y, year; TR, treatments. *$P < 0.05$; **$P < 0.01$; ns: non-significance.

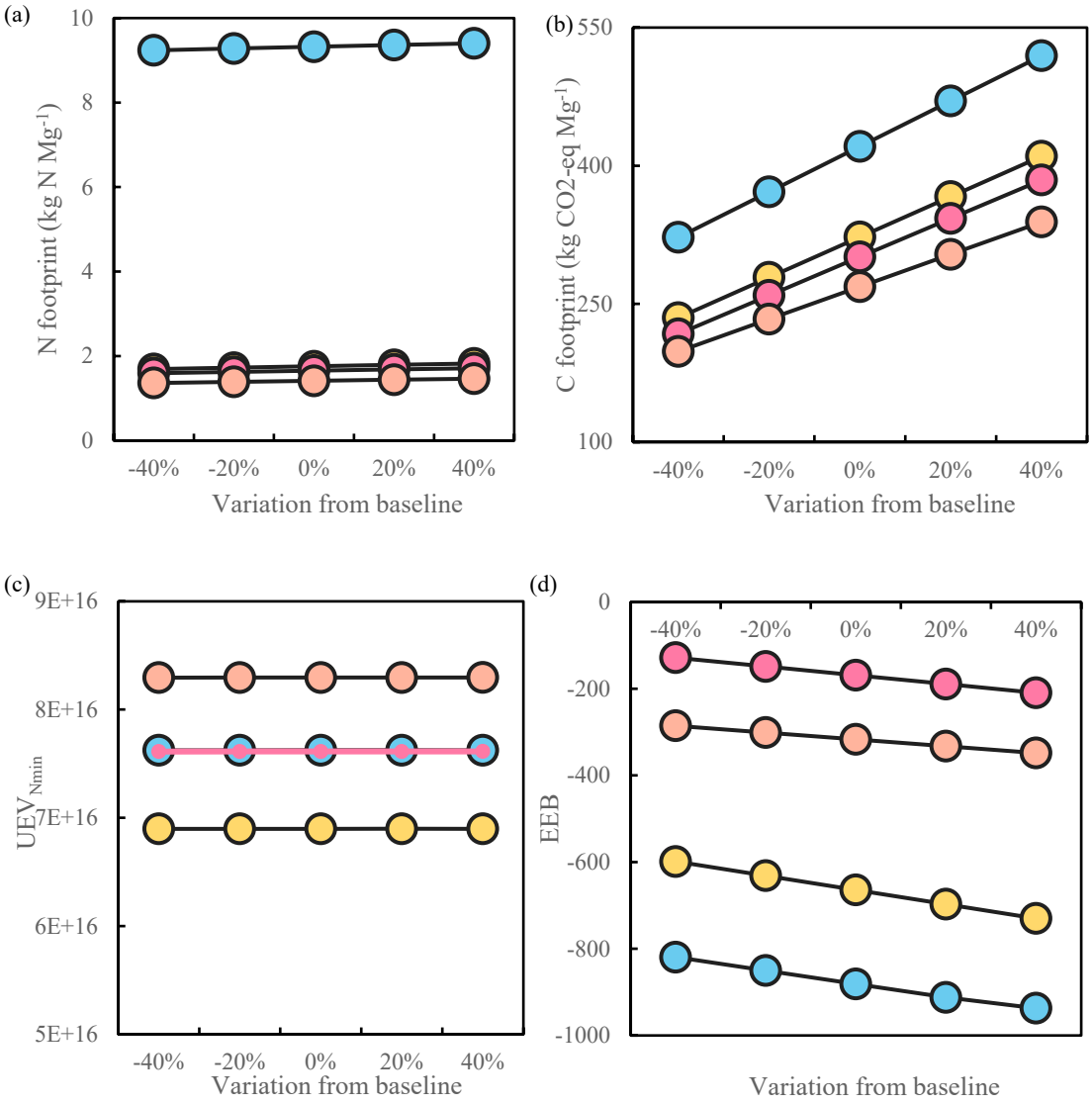


Fig. S4 Sensitivity to key parameters with N footprint (a),C footprint (b), UEVNmin (c) and EEB (d)