Table S1 Comparison of agronomic practices and machinery inputs for winter wheat under cooperative system (CM) and smallholder system (SM)

	Cooperative system (CM)	Smallholder system (SM)
Field preparation	Whole straw chopping and returning; rotary tillage with a 120-hp tractor	Whole straw chopped and returned; rotary tillage with a 40-hp tractor
Chemical fertilizer	Compound fertilizers and urea	Compound fertilizers and urea
Fertilizer application method	Mechanical-applied fertilization	Hand-applied fertilization
N application rate (basal: topdressing)	240 kg ha^{-1} (40% : 60%)	275 kg ha^{-1} (50% : 50%)
P application rate	120 kg ha^{-1} (100% : 0%)	150 kg ha^{-1} (100% : 0%)
K application rate	120 kg ha^{-1} (100% : 0%)	150 kg ha^{-1} (100% : 0%)
Irrigation method	Drip irrigation	Drip irrigation
Crop protection application method	Drone spraying	Knapsack sprayer
Harvest method	175-hp combine harvester	175-hp combine harvester

Table S2 Inputs for winter wheat under cooperative system (CM) and smallholder system (SM)

		2022-2023		2023-2024		2024-2025	
		CM	SM	CM	SM	CM	SM
Human labor	h/ ha^{-1}	110	176	144	216	155	236
Wheat seed	kg/ ha^{-1}	140	160	140	160	140	160
N fertilizer	kg/ ha^{-1}	240	275	240	275	240	275
P fertilizer	kg/ ha^{-1}	120	150	120	150	120	150
K fertilizer	kg/ ha^{-1}	120	150	120	150	120	150
Fungicide	kg/ ha^{-1}	1.40	1.56	1.40	1.56	1.40	1.56
Herbicides	kg/ ha^{-1}	0.54	0.60	0.54	0.60	0.54	0.60
Insecticide	kg/ ha^{-1}	0.95	1.05	0.95	1.05	0.95	1.05
Water	m^3/ ha^{-1}	900	1200	2250	2400	2700	3000
Diesel	L/ ha^{-1}	86	95	86	95	86	95
Farm machinery	h/ ha^{-1}	19	21	19	21	19	21

Table S3 Grain yield, biomass yield, total input cost, gross return , net income and net benefit–cost ratio (NBCR) for winter wheat under cooperative system (CM) and smallholder system (SM)

	Grain yield/ kg ha^{-1}		Biomass yield/ kg ha^{-1}		Total input cost/ CNY ha^{-1}		Gross return / CNY ha^{-1}		Net income/ CNY ha^{-1}		NBCR	
	CM	SM	CM	SM	CM	SM	CM	SM	CM	SM	CM	SM
2022-2023	9447±101a	9165±48b	24221±389a	23558±307b	9377	11561	21351±228a	20712±108b	11974±228a	9151±108b	1.28±0.02a	0.79±0.01b
2023-2024	10657±184	10365±87b	27280±338a	26623±345b	10847	13301	24085±417a	23424±196b	13238±417a	10124±196b	1.22±0.04a	0.76±0.01b
2024-2025	10573±102	10193±200b	27059±444a	26210±288b	11120	13831	23896±232a	23036±452b	12776±232a	9205±452b	1.15±0.02a	0.67±0.03b

Note: Values are means ± standard deviations of three independent fields per management system (n = 3). Different lowercase letters indicate significant differences between CM and SM within the same growing season for the same variable ($P < 0.05$). NBCR, net benefit–cost ratio, calculated as net return divided by total input cost.

Table S4 Endpoint environmental impacts of wheat production under cooperative management (CM) and smallholder management (SM)

Factors	Unit	CM	SM
Human Health	Pt	367	416
Ecosystems	Pt	25.4	28.8
Resources	Pt	212	239
Total	Pt	604.4	683.8

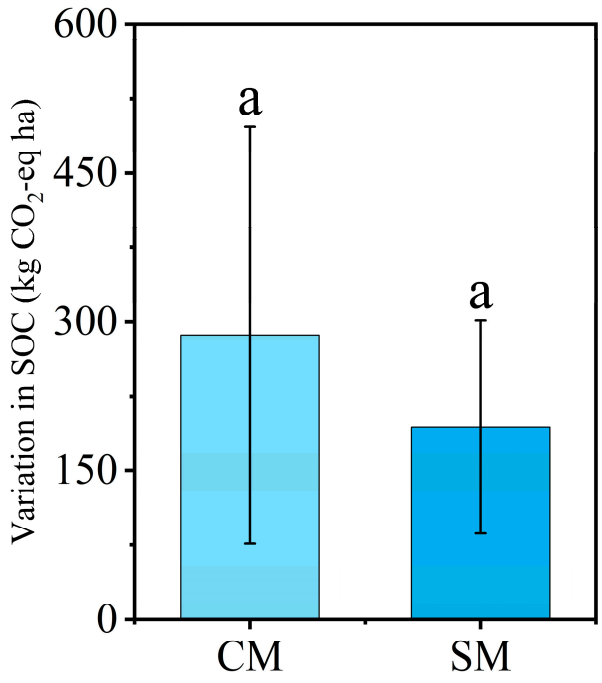


Figure S1 Variation in soil organic carbon of winter wheat under smallholder management (SM) and cooperative management (CM)