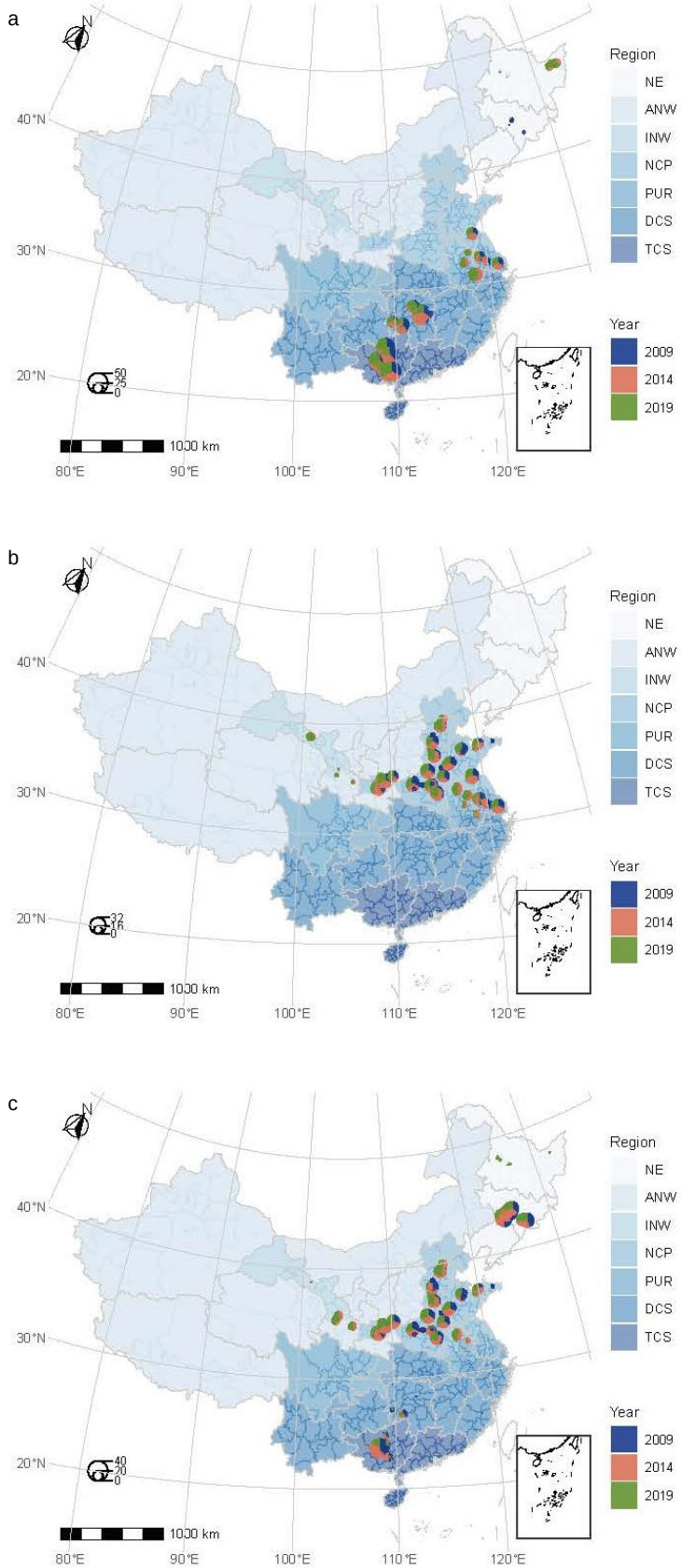
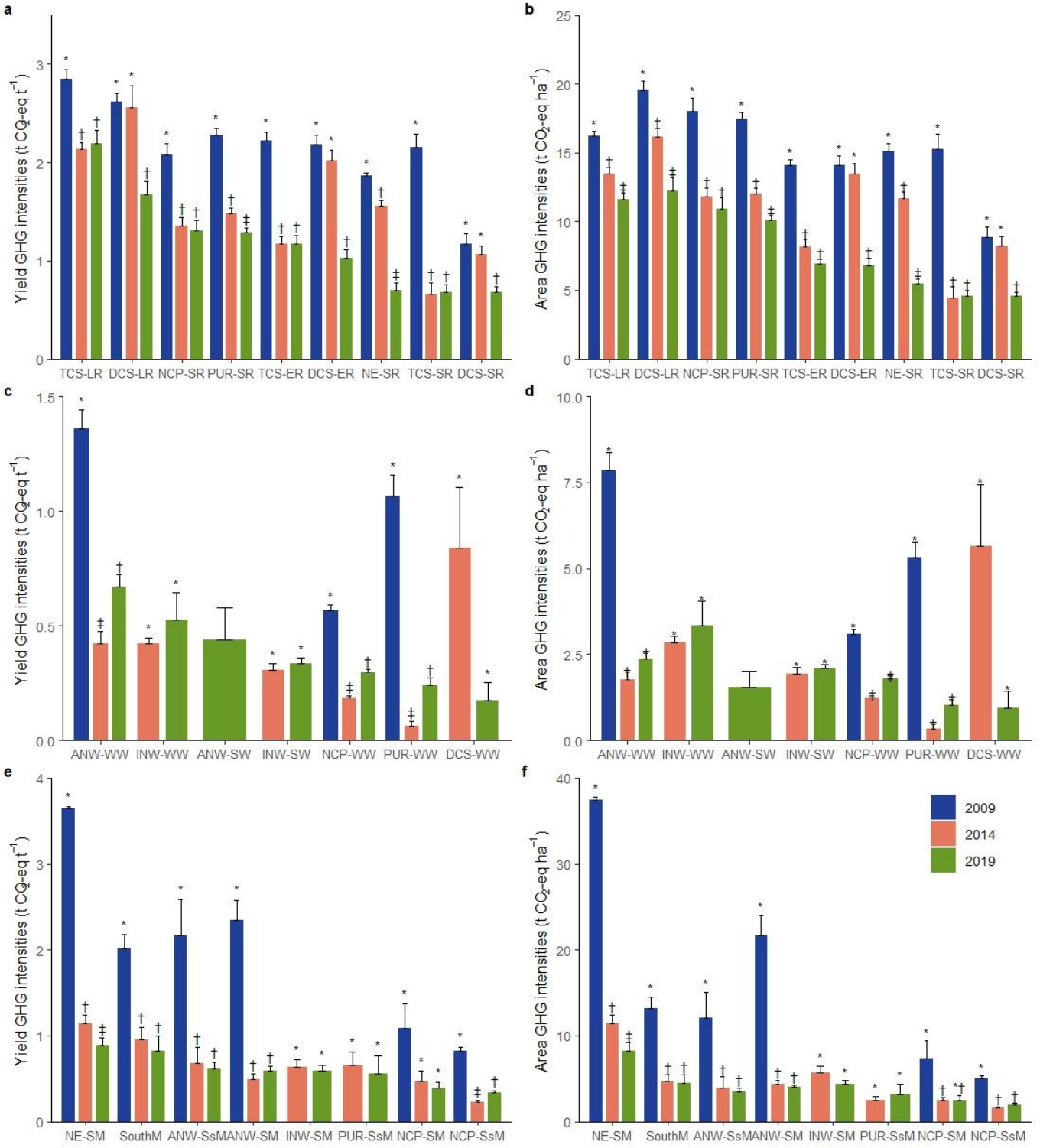
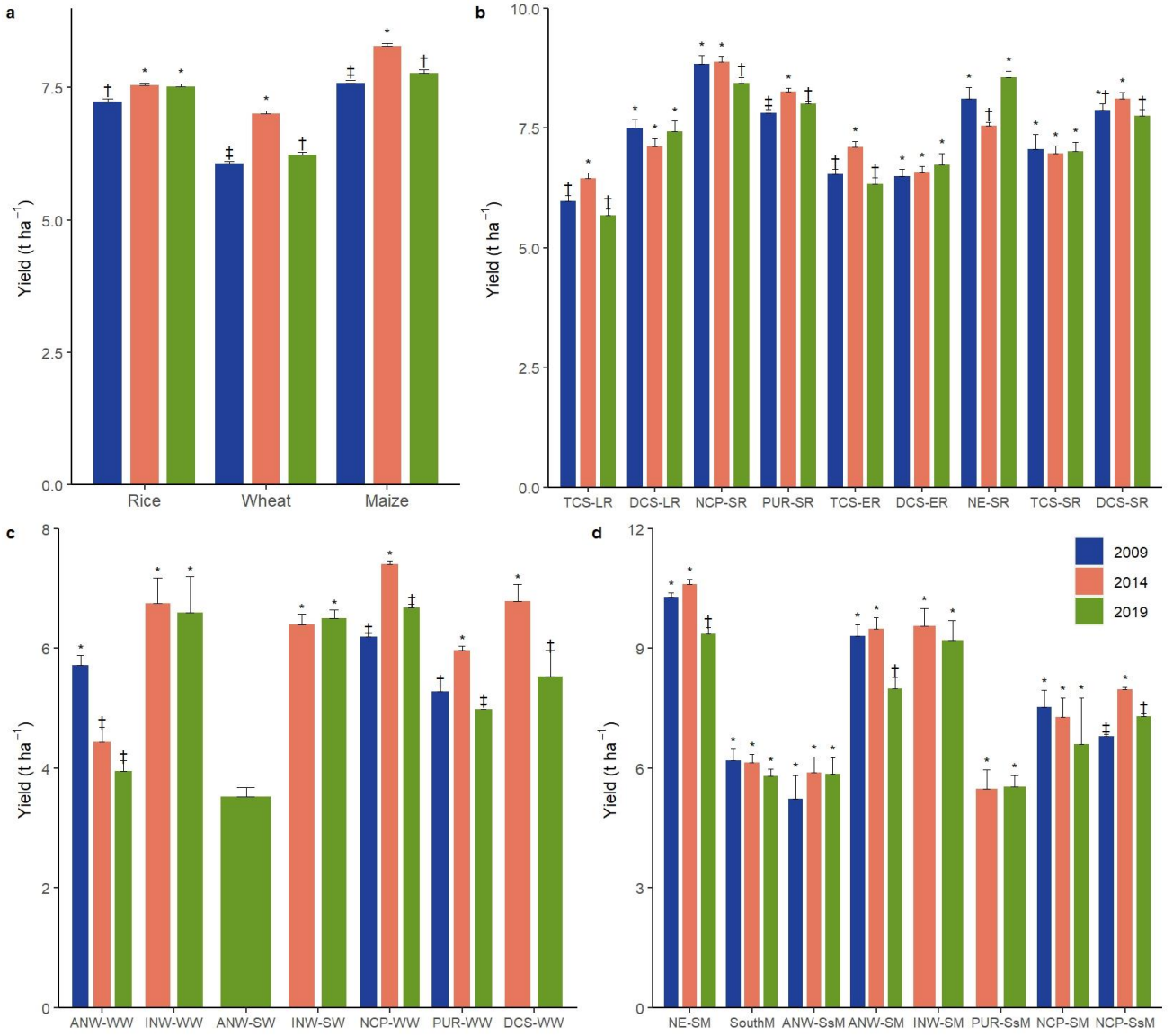


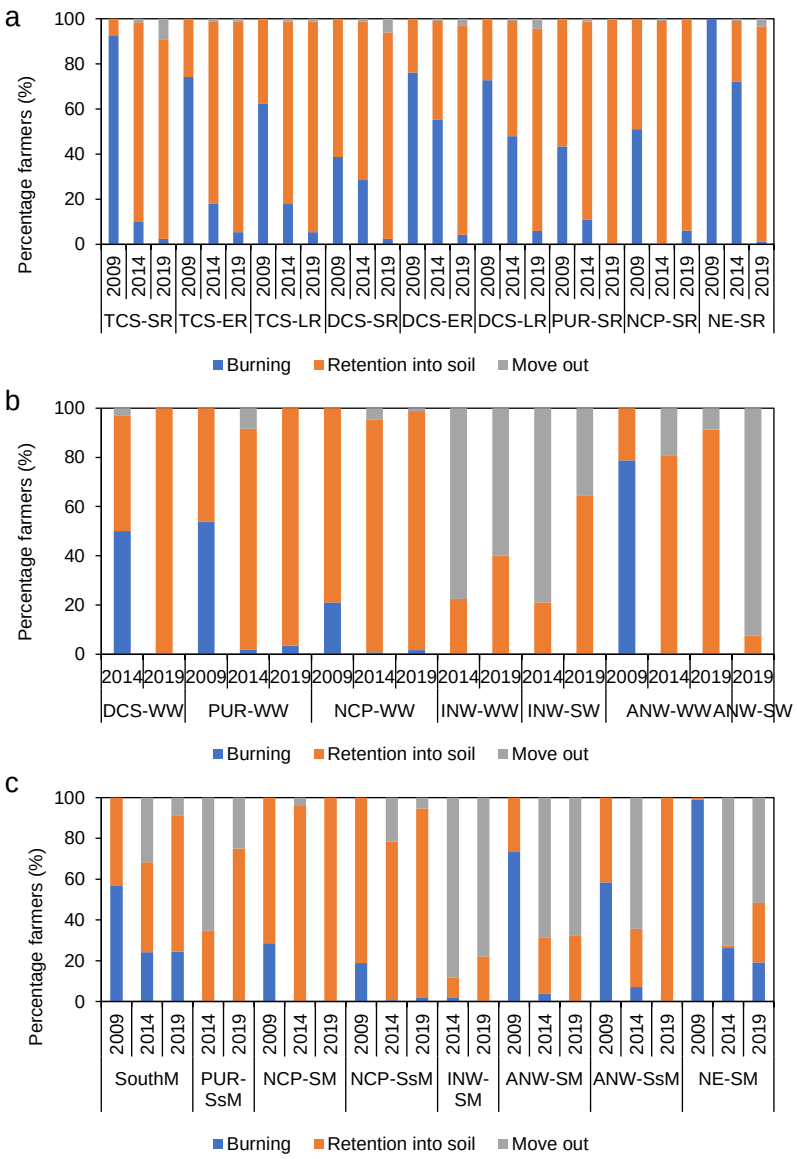
Extended Data Figure 1 Distribution of small-holder communities for grain tracked from 2009 to 2019 in China. a, Rice (n=2454); b, wheat (n=3273); and c, maize (n=3657). The diameter of the pie chart represents the total of the 2009-2019 samples for each small-holder communities, while the 2009, 2014, and 2019 sample shares are the proportion of blue, orange, and green hues in the pie chart. Different shades of blue indicate the 7 divisions of China, excluding Taiwan, Hong Kong and Macau. The region codes used were as follows: TCS=triple-cropping area in South China, DCS= double-cropping rice area in South China, PUR = lower basin of the Yangtze River (paddy–upland rotation area), NCP=North China Plain, INW=irrigated area in Northwest China; ANW=arid area in Northwest China, and NE=single crop area in Northeast China.



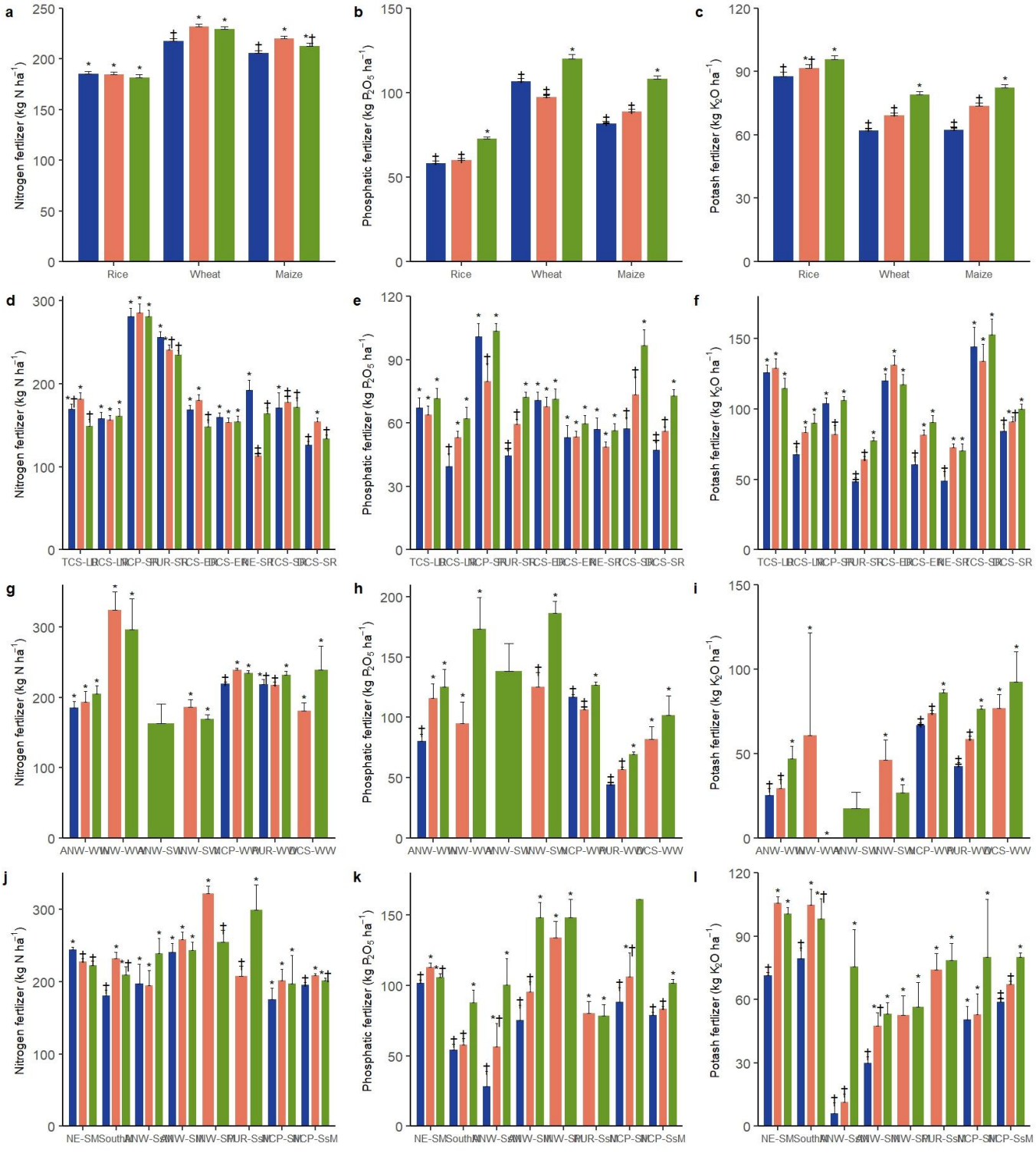
Extended Data Figure 2 Average GHG intensities per yield (t CO2-eq t^{-1}) and average GHG intensities per hectare (t CO2-eq ha^{-1}) of rice (a, b), wheat (c, d) and maize (e, f) at the regional scale from 2009–2019. Crop codes: ER=early rice, LR=later rice, SR=single rice, WW= winter wheat, SW=spring wheat, SM=spring maize, SsM=summer maize, SouthM=maize in southern China. The region codes used were as follows: TCS=triple-cropping area in South China, DCS= double-cropping rice area in South China, PUR = lower basin of the Yangtze River (paddy–upland rotation area), NCP=North China Plain, INW=irrigated area in Northwest China; ANW=arid area in Northwest China, and NE=single crop area in Northeast China. The means ± s.e.m.s followed by the same footnote symbol(s) for each crop in different areas are not significantly different at $P<0.05$. ANOVA was not performed when the sample size was less than 3.



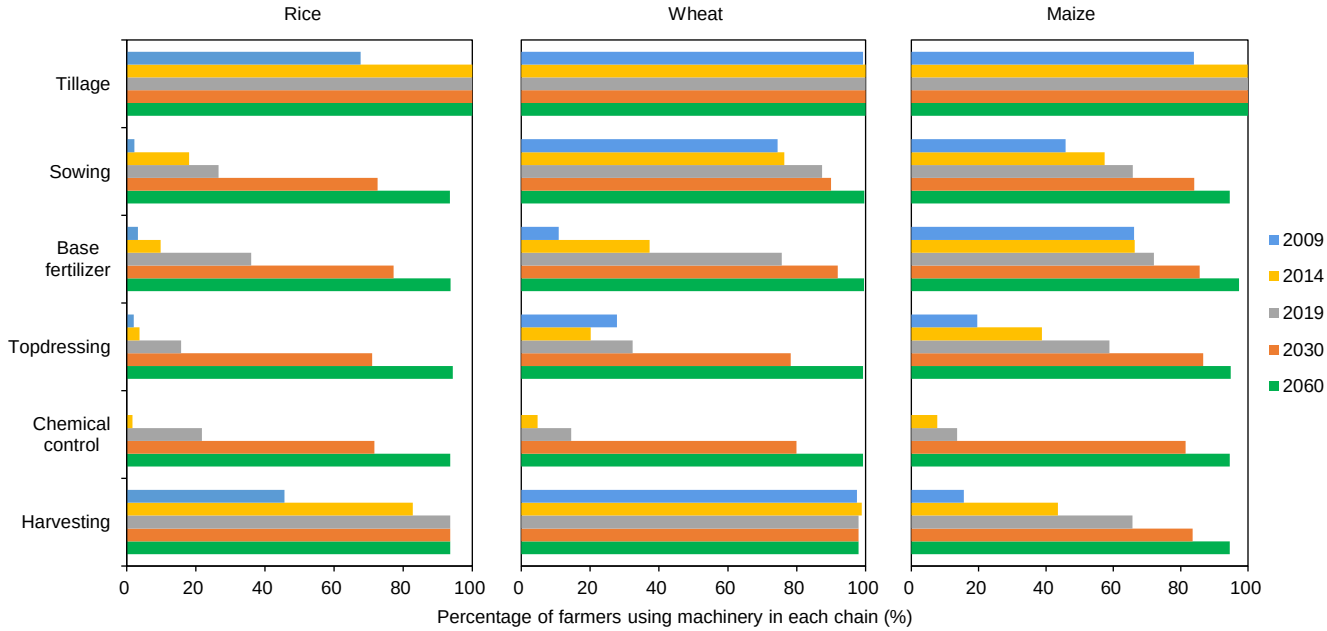
Extended Data Figure 3 Average yield per unit area (t ha^{-1}) of three crops at the national scale (a) and at the regional scale for rice (b), wheat (c) and maize (d). Crop codes: ER=early rice, LR=later rice, SR=single rice, WW= winter wheat, SW=spring wheat, SM=spring maize, SsM=summer maize, SouthM=maize in southern China. The region codes used were as follows: TCS=triple-cropping area in South China, DCS=double-cropping rice area in South China, PUR=lower basin of the Yangtze River (paddy–upland rotation area), NCP= North China Plain, INW=irrigated area in Northwest China; ANW=arid area in Northwest China, and NE=single crop area in Northeast China. The means ± s.e.m.s followed by the same footnote symbol(s) for each crop (area crops) are not significantly different at $P<0.05$. ANOVA was not performed when the sample size was less than 3.



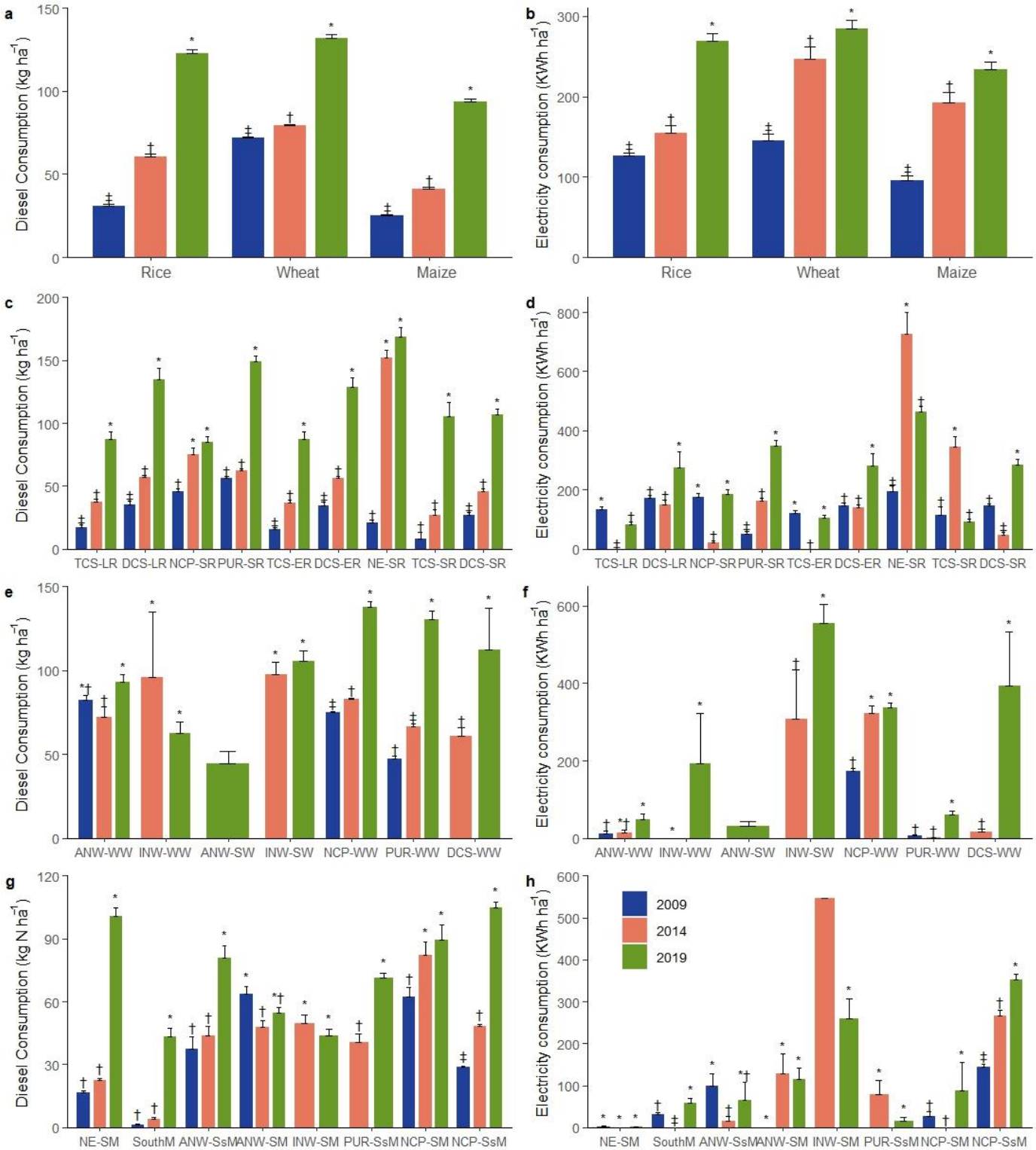
Extended Data Figure 4 Changes in the straw treatment method used for rice (a), wheat (b) and maize (c) at the regional scale. Crop codes: ER=early rice, LR=later rice, SR=single rice, WW= winter wheat, SW=spring wheat, SM=spring maize, SsM=summer maize, SouthM=maize in southern China. The region codes used were as follows: TCS = triple-cropping area in South China; DCS= double-cropping rice area in South China; PUR=lower basin of the Yangtze River (paddy–upland rotation area); NCP= North China Plain; INW=irrigated area in Northwest China; ANW=arid area in Northwest China; and NE=single crop area in Northeast China.



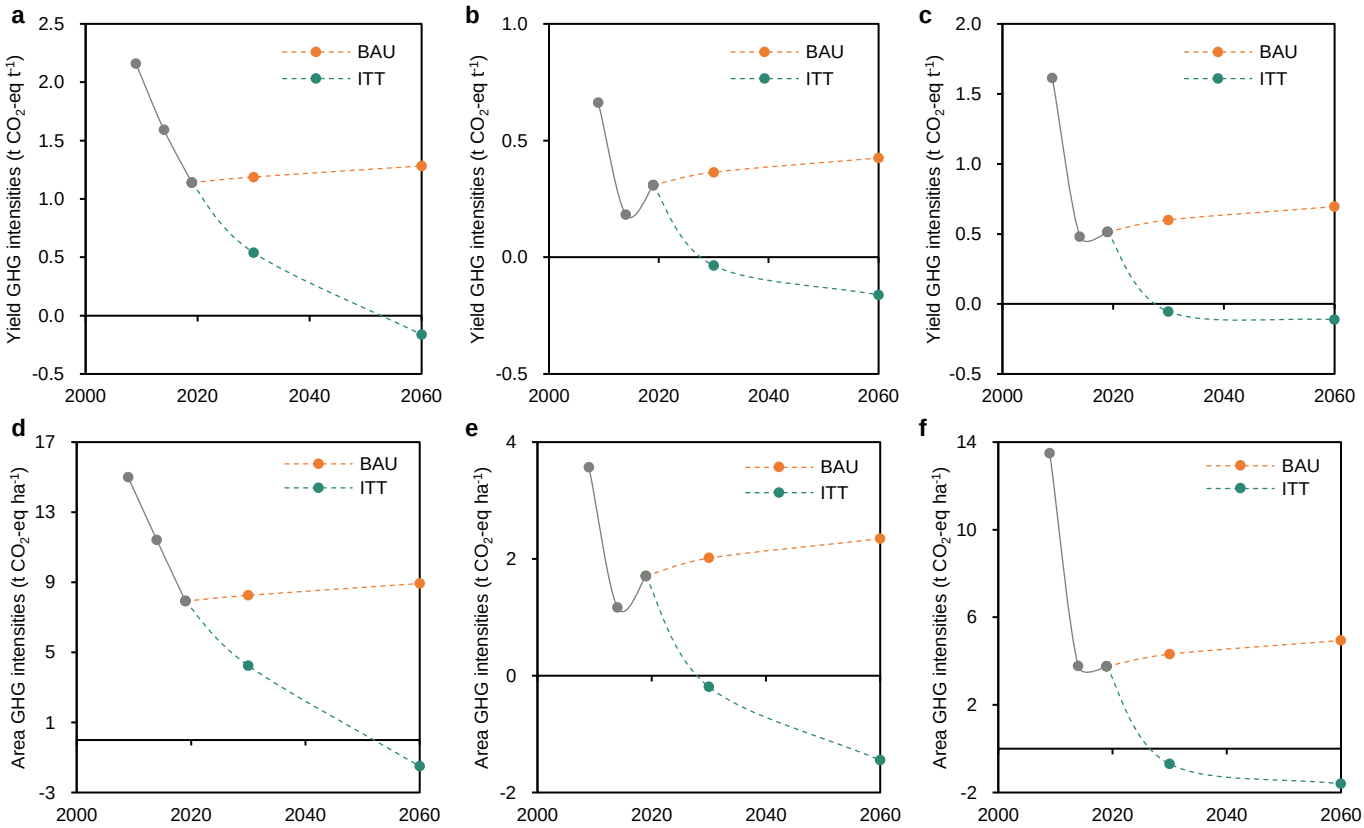
Extended Data Figure 5 Average nitrogen, phosphate and potash fertilizer usages (kg ha^{-1}) of three crops at the national scale (a, b, c) and at the regional scale for rice (d, e, f), wheat (g, h, i) and maize (j, k, l). Crop codes: ER=early rice, LR=later rice, SR=single rice, WW= winter wheat, SW=spring wheat, SM=spring maize, SsM=summer maize, SouthM=maize in southern China. The region codes used were as follows: TCS=triple-cropping area in South China, DCS=double-cropping rice area in South China, PUR=lower basin of the Yangtze River (paddy–upland rotation area), NCP=North China Plain, INW=irrigated area in Northwest China; ANW=arid area in Northwest China, and NE=single crop area in Northeast China. The means ± s.e.m.s followed by the same footnote symbol(s) for each crop (area crops) are not significantly different at $P<0.05$. ANOVA was not performed when the sample size was less than 3.



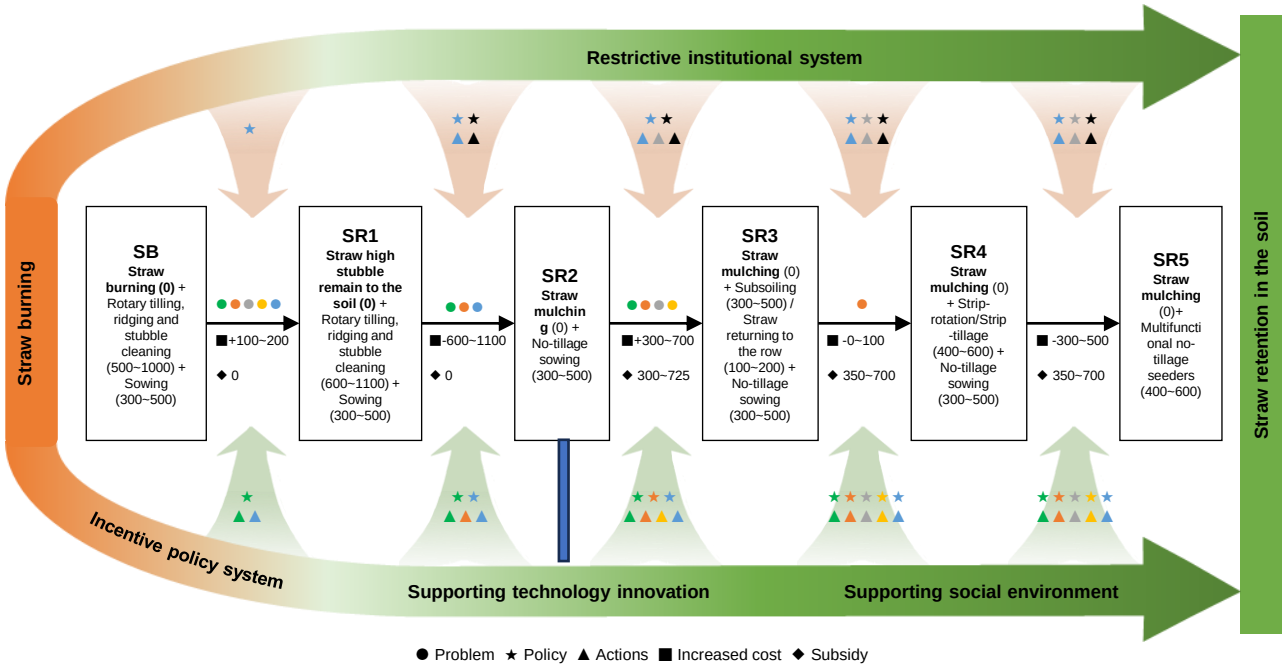
Extended Data Figure 6 Mechanization technology adoption rate of rice, wheat and maize per process at the national scale.



Extended Data Figure 7 Average diesel consumption and electricity consumption of the three major crops at the national scale (a, b) and at the regional scale for rice (c, d), wheat (e, f) and maize (g, h). Crop codes: ER=early rice, LR=later rice, SR=single rice, WW= winter wheat, SW=spring wheat, SM=spring maize, SsM=summer maize, SouthM=maize in southern China. The region codes used were as follows: TCS = triple-cropping area in South China; DCS= double-cropping rice area in South China; PUR = lower basin of the Yangtze River (paddy–upland rotation area); NCP = North China Plain; INW = irrigated area in Northwest China; ANW= arid area in Northwest China; and NE= single crop area in Northeast China. The means ± s.e.m.s followed by the same footnote symbol(s) for each crop (area crops) are not significantly different at $P<0.05$. ANOVA was not performed when the sample size was less than 3.



Extended Data Figure 8 Average yield GHG intensities and area GHG intensities of rice (a, d), wheat (b, e) and maize (c, f) under the BAU and IIT scenarios in 2030 and 2060. The gray dots are the actual observed data from 2009 to 2019. The orange dots are in the business as usual (BAU) scenario for 2030 and 2060, and the green dots are in the integrated innovative technologies (ITT) scenario for 2030 and 2060. The definitions of the scenarios are detailed in Supplementary Method 2.5.



Extended Data Figure 9 The dual drive of technology and policy has made it a reality to move from straw burning to straw retention in the soil[, and also established restrictive institutional system, incentive policy system, supporting technology innovation environment and supporting social environment. In this figure, dot (●), pentagram (★) and triangle (▲) indicate the problems (e.g. regional appropriateness of technology, no-tillage machinery, farmers' awareness, etc.), policies (e.g. no-burning policies, subsidies, policies for cultivation of new business entities, etc.), and actions from many actors (e.g. technology research and development, propaganda, demonstration, training, etc., machinery research and development, upgrading, production and sales, etc., mechanization services, etc.) in the technological innovation from straw burning to straw remain into the soil, respectively. The colors of dot, pentagram and triangle - green, orange, grey, yellow, blue and black correspond to the five elements of technological innovation - Natural resources, Material resources, Capital, Labor, Knowledge, and technology supervision, respectively. The number in parentheses is the cost of the operation in RMB ha-1. The numbers behind the squares (■) and diamonds (◆) are the increased costs and available subsidies for farming and sowing, respectively, and the plus or minus sign in front of the number indicates an increase or decrease in cost, when transforming straw burning to straw remaining in the soil. SB and SR1~SR5 denote straw burning and different stages of straw return technology, respectively.

Extended Data Table 1 Differences in area GHG intensities, yield GHG intensities, yield, total cost and net profit of maize, wheat and rice between straw returned to soil and not returned to soil after PSM analysis.

Indicators	Crops	2009			2014			2019		
		Straw returned to soil	Straw not returned to soil	Difference (ATT)	Straw returned to soil	Straw not returned to soil	Difference (ATT)	Straw returned to soil	Straw not returned to soil	Difference (ATT)
Area GHG intensities (t CO_2-eq ha^{-1})	Maize	0.91	23.89	-22.97***	0.88	5.00	-4.12***	1.24	10.75	-9.50***
	Wheat	0.90	10.87	-9.97***	0.86	4.88	-4.02***	1.49	8.52	-7.03***
	Rice	9.08	18.95	-9.87***	8.37	19.75	-11.38***	7.65	13.56	-5.91***
Yield GHG intensities (t CO_2-eq t^{-1})	Maize	0.18	3.58	-3.40***	0.13	0.77	-0.63***	0.23	1.61	-1.38***
	Wheat	0.18	1.93	-1.75***	0.14	0.73	-0.60***	0.26	1.46	-1.20***
	Rice	1.28	2.71	-1.43***	1.20	2.74	-1.54***	1.09	2.03	-0.95***
Yield (t ha^{-1})	Maize	6.83	6.82	0.01	7.91	7.56	0.35*	7.41	7.70	-0.29
	Wheat	6.24	5.71	0.53***	7.03	6.82	0.22	6.36	5.86	0.50
	Rice	7.44	7.16	0.28**	7.60	7.29	0.31***	7.57	6.86	0.71*
Total cost (10^3 yuan ha^{-1})	Maize	10.64	10.38	0.27	15.1	15.9	-0.80*	15.27	17.07	-1.81**
	Wheat	11.11	9.46	1.64***	15.72	14.82	0.90*	16.19	14.65	1.54*
	Rice	11.99	11.97	0.02	16.8	15.23	1.57***	18.54	20.68	-2.14
Net profit (10^3 yuan ha^{-1})	Maize	0.49	0.30	0.19	2.43	0.52	1.91***	-2.78	-3.89	1.10
	Wheat	0.21	0.10	0.11	0.42	0.57	-0.15	-2.11	-1.39	-0.72
	Rice	2.42	2.06	0.36	3.25	3.77	-0.52	0.52	-1.08	1.60

T tests were performed between the straw treatments for each crop in 2009-2019, ***P < 0.01, **P < 0.05, *P < 0.1, no symbol(s) not significant.