Table S1. Description of the experimental treatments

Treatment Code	Group treatment	Mineral nitrogen fertilizer-NF (kg ha^{-1})	Organic fertilizer-ORF	Fertilizer application
0	Control	0	0	0
1.1	NPK	35	0	MF
1.2		70		
1.3		105		
1.4		140		
1.5		175		
2.1	NPK+fym1	35	1.2 t ha^{-1} year^{-1} DM farmyard manure	fym1
2.2		70		
2.3		105		
2.4		140		
2.5		175		
3.1	PK+fym2	0	3.2 t ha^{-1} year^{-1} DM farmyard manure	fym2
3.2	NPK+fym2	35		
3.3		70		
3.4		105		
3.5		140		
4.1	NPK+Straw	35	2.0 t ha^{-1} year^{-1} DM straw	straw
4.2		70		
4.3		105		
4.4		140		
4.5		175		

Treatment codes (1.1-1.5; 2.1-2.5; 4.1-4.5): each rate of mineral nitrogen fertilizer-NF (five levels NF: 35, 70, 105, 140, 175 kg ha^{-1}, respectively) with organic fertilizer-ORF (three types: no ORF, 1.2 t dry mass (DM) ha^{-1} farmyard manure (FYM) and 2.0 t DM ha^{-1} straw). Treatment codes (3.1-3.5): each 3.2 t DM ha^{-1} FYM with each NF level (five levels: 0, 35, 70, 105, and 140 kg ha^{-1}, respectively). Treatment code "0" or control: no fertilizer inputs. Fertilizer application (MF application: sole mineral fertilizer applied at 35, 70, 105, 140 and 175 kg ha^{-1} N; fym1: FYM applied at 35, 70, 105, 140 and 175 kg ha^{-1} N; fym2: FYM applied at 0, 35, 70, 105 and 140 kg ha^{-1} N; straw: straw applied at 35, 70, 105, 140 and 175 kg ha^{-1} N.

Table S2. Cropping sequencing in the long-term experiment (LTFE) "V140". In bold: Winter wheat (WW), in grey: preceding crops

Harvest year	Crop	Harvest year	Crop	Harvest year	Crop
1963	Maize	1981	Sugar beet	1999	Potato
1964	Winter rye	1982	Spring barley	2000	Spring barley
1965	Potato	1983	Potato	2001	Pea
1966	Winter rye	**1984**	**Winter wheat**	**2002**	**Winter wheat**
1967	Potato	1985	Sugar beet	2003	Maize
1968	Summer wheat	1986	Spring barley	2004	Winter rye
1969	Sugar beet	1987	Potato	2005	Flax
1970	Spring barley	**1988**	**Winter wheat**	2006	Winter rye
1971	Maize	1989	Sugar beet	2007	Potato
1972	Winter rye	1990	Spring barley	2008	Spring barley
1973	Potato	1991	Potato	2009	Pea
1974	**Winter wheat**	**1992**	**Winter wheat**	**2010**	**Winter wheat**
1975	Sugar beet	1993	Sugar beet	2011	Maize
1976	Spring barley	**1994**	**Winter wheat**	2012	Winter rye
1977	Sugar beet	1995	Maize	2013	Flax
1978	Spring barley	1996	Winter rye	2014	Winter rye
1979	Sugar beet	1997	Flax	2015	Potato
1980	Spring barley	1998	Winter rye	2016	Spring barley

Thai *et al.* (36) adapted

The position of WW within the crop system was changed during the LTFE. There were different WW crop rotations: potato-WW-sugar beet (04 rounds), sugar beet-WW-maize (01 round), pea-WW-maize (02 rounds). Between 1975-1982, no WW was seeded.

Table S3. Selected chemical soil parameters in the topsoil (0-25 cm) of each treatment in four WW seasons (1984, 1988, 1992, and 1994)

Treatment code	pH (KCl)	Total N (mg/100g soil)	SOC (mg/100g soil)	P (mg/100g soil)	K (mg/100g soil)	Mg ($CaCl_2$) (mg/100g soil)
0	6.3^{g}	39.7^{a}	440.4^{a}	6.5^{a}	9.5^{a-e}	5.0^{ab}
1.1	6.2^{fg}	42.8^{ab}	470.2^{ab}	8.0^{ab}	11.3^{b-f}	5.0^{ab}
1.2	6.1^{efg}	42.9^{ab}	486.6^{a-d}	7.9^{ab}	10.0^{a-e}	4.7^{ab}
1.3	6.1^{c-g}	43.5^{abc}	480.6^{abc}	7.5^{ab}	9.4^{abc}	4.7^{ab}
1.4	6.0^{a-e}	44.2^{a-d}	490.8^{a-d}	7.6^{ab}	8.7^{a}	4.6^{ab}
1.5	5.9^{a-d}	45.0^{a-d}	498.1^{a-e}	8.0^{ab}	9.2^{ab}	4.4^{a}
2.1	6.3^{g}	46.8^{bcd}	507.1^{b-e}	9.0^{bdc}	11.4^{b-g}	4.8^{ab}
2.2	6.1^{b-g}	46.9^{bcd}	523.0^{b-e}	8.5^{bc}	10.2^{a-e}	4.5^{ab}
2.3	6.0^{a-e}	50.3^{d-h}	559.1^{e-h}	9.0^{b-e}	10.0^{a-e}	4.6^{ab}
2.4	6.0^{a-e}	49.3^{b-g}	548.8^{d-g}	8.9^{bdc}	10.0^{a-e}	4.5^{ab}
2.5	5.8^{a}	49.9^{c-g}	548.6^{d-g}	8.8^{bcd}	9.3^{abc}	4.4^{a}
3.1	6.1^{d-g}	50.5^{d-h}	548.2^{d-g}	10.8^{ef}	13.7^{g}	4.6^{ab}
3.2	6.1^{d-g}	56.8^{h}	618.3^{h}	11.0^{f}	13.0^{fg}	4.8^{ab}
3.3	6.1^{d-g}	55.4^{gh}	604.1^{fgh}	10.8^{ef}	11.9^{d-g}	5.0^{ab}
3.4	6.0^{a-e}	54.4^{fgh}	608.4^{gh}	10.2^{c-f}	11.6^{c-g}	4.8^{ab}
3.5	5.8^{ab}	54.0^{e-h}	596.1^{fgh}	10.4^{def}	10.8^{a-f}	4.5^{ab}
4.1	6.1^{d-g}	48.5^{b-f}	539.1^{c-f}	8.3^{ab}	11.9^{efg}	5.2^{b}
4.2	6.1^{d-g}	46.8^{bcd}	522.5^{b-e}	8.4^{bc}	10.5^{a-e}	4.7^{ab}
4.3	6.0^{a-f}	47.7^{b-e}	545.2^{c-g}	8.1^{ab}	10.3^{a-e}	4.8^{ab}
4.4	5.9^{a-e}	48.6^{b-f}	549.9^{d-g}	8.3^{ab}	9.8^{a-e}	4.7^{ab}
4.5	5.9^{abc}	48.0^{b-f}	543.5^{c-g}	8.2^{ab}	8.7^{a}	4.5^{ab}

Total nitrogen: total N; organic carbon: SOC; plant-available phosphorus: P (mg/100g soil); plant-available potassium: K (mg/100g soil); plant-available magnesium: Mg ($CaCl_2$) (mg/100g soil). Means sharing the same letters in the same column are not significantly different ($P < 0.05$). Treatments codes are given in Table S1.

Table S4: Analyzed input variables for their effects on the grain yield of winter wheat by LMM and M5P models

Input variable name	**Unit**
Fertilizers applied	
1. Mineral nitrogen fertilizer	kg ha^{-1}
2. Farmyard manure fertilizer	tons
3. Straw	tons
Monthly weather during the growing season	
4. Monthly mean temperature	°C
5. Cumulative freeze days in a month,	day
6. Cumulative days Tmax > 30°C in a month	day
7. Cumulative precipitation	mm
8. Growing degree days (GDD).	GDD
Soil	
9. Total nitrogen in soil	mg/100 g soil
10. Soil organic carbon	mg/100 g soil
Crop yield	
11. Winter rye	Mg DM ha^{-1}
12. Potatoes	Mg DM ha^{-1}
13. Sugar beets	Mg DM ha^{-1}
14. Pea	Mg DM ha^{-1}
Preceding crop	
15. Potatoes	None
16. Sugar beets	None
17 Pea	None

Table S5a. Average monthly temperature during WW growing season in the trial years

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
1973/74	13.6	7	3.1	0	2.5	3.1	4.6	7.6	11.3	14.8	16
1983/84	14.2	9.3	3.6	0	1	-0.6	1.9	7.6	12.6	14.1	16.1
1987/88	14	9.2	5.5	1.9	2.9	2.5	2.3	8.2	15.2	15.8	18.3
1991/92	14.7	7.9	3.6	0.8	0.4	2.9	4.4	8.3	14.9	18.8	19.9
1993/94	12	7.6	-1.1	2.4	2.5	-2.1	5	8.4	12.2	15.4	21.4
2001/02	12.5	12.4	3.8	-0.4	1.5	4.8	4.9	8.1	15.1	17.1	19.1
2009/10	14.9	7.5	6.9	-0.5	-5.9	-0.8	4.3	8.7	11	16.8	21.5
Mean	13.7	8.7	3.6	0.6	0.7	1.4	3.9	8.1	13.2	16.1	18.9
SD	1.1	1.8	2.5	1.1	3.0	2.5	1.3	0.4	1.8	1.6	2.3
CV	0.08	0.21	0.68	1.91	4.35	1.82	0.32	0.05	0.14	0.10	0.12
Max	14.9	12.4	6.9	2.4	2.9	4.8	5.0	8.7	15.2	18.8	21.5
Min	12.0	7.0	-1.1	-0.5	-5.9	-2.1	1.9	7.6	11.0	14.1	16.0

Sep to Jul is the short form of the month from September to July. SD: standard deviation; CV: coefficient variation; Max: maximum, Min: minimum.

Table S5b: Average monthly precipitation during WW growing season in the trial years

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
1973/74	24.7	60.2	47.8	49	29.9	42.9	10.5	17.4	46.6	74.8	62.4
1983/84	28.4	35.7	43.2	60.9	65.6	29.2	4.2	36.7	61.1	80.3	26.5
1987/88	72.4	10.2	52.5	47.6	44.4	83.4	65.7	1.6	23	116.9	33.6
1991/92	13.3	31.6	51.6	43.3	18	26.9	74.3	34.7	14	19.2	35.5
1993/94	73.3	22.8	37.4	105.8	81.3	7.3	88.1	48.3	88.5	35.5	45.4
2001/02	125.7	39.4	25.3	20.6	36.8	75.7	48.2	48.5	60.7	35.7	66.5
2009/10	38.3	79	63.8	42.4	12.7	13	33	22.9	85.6	5.4	131
Mean	53.7	39.8	45.9	52.8	41.2	39.8	46.3	30.0	54.2	52.5	57.3
SD	39.3	23.1	12.3	26.3	24.9	29.6	32.0	17.1	28.6	39.4	35.8
CV	0.73	0.58	0.27	0.50	0.60	0.74	0.69	0.57	0.53	0.75	0.62
Max	125.7	79.0	63.8	105.8	81.3	83.4	88.1	48.5	88.5	116.9	131.0
Min	13.3	10.2	25.3	20.6	12.7	7.3	4.2	1.6	14.0	5.4	26.5

Sep to Jul is the short form of the month from September to July. SD: standard deviation; CV: coefficient variation; Max: maximum, Min: minimum.

Table S5c: Cumulative freezing days (freezing days) and the cumulative number of days recorded having temperatures above 30°C (days Tmax > 30°C) in selected months during winter wheat growing season in the trial years

	Freezing days					Days Tmax > 30°C	
Year	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Jun**	**Jul**
1973/74	6.0	12.0	7.0	4.0	0.0	0.00	0.00
1983/84	7.0	13.0	10.0	15.0	9.0	0.00	4.00
1987/88	0.0	14.0	5.0	3.0	6.0	0.00	2.00
1991/92	1.0	8.0	11.0	3.0	0.0	2.00	6.00
1993/94	14.0	4.0	3.0	15.0	1.0	2.00	14.00
2001/02	2.0	15.0	12.0	4.0	0.0	1.00	5.00
2009/10	0.0	14.0	30.0	17.0	8.0	0.00	11.00
Mean	4.3	11.4	11.1	8.7	3.4	0.7	6.0
SD	5.1	4.0	8.9	6.6	4.1	1.0	4.9
CV	1.20	0.35	0.80	0.75	1.19	1.33	0.82
Max	14.0	15.0	30.0	17.0	9.0	2.0	14.0
Min	0.0	4.0	3.0	3.0	0.0	0.0	0.0

Sep to Jul is the short form of the month from September to July. SD: standard deviation; CV: coefficient variation; Max: maximum, Min: minimum.

Table S6: Pearson's correlation of fixed effects in the LMM

	(Intr)	NF	N in soil	pcrp_y	Tmd_Oc	Tm30_J	Frz_Dc	Frz_Fb
NF	-0.460							
N in soil		-0.237	-0.074					
pcrop_yield	-0.283	-0.156	0.432					
Tmid_Oct	-0.383	-0.067	0.375	0.421				
Tmax30_Jul	-0.012	0.105	-0.273	-0.674	-0.591			
Freeze_Dec	-0.143	-0.006	-0.490	0.065	-0.500	0.368		
Freeze_Feb	-0.127	-0.071	0.297	0.451	0.625	-0.818	-0.444	
Preci_Jun	-0.014	0.112	0.004	-0.730	-0.353	0.787	-0.105	-0.480

NF: Nitrogen fertilizer rate; pcrop_yield: preceding crop yield; Tmid_Oct: Temperature in October; Tmax30_July: cumulative number of days in July with maximum temperatures above 30°C; Freeze_Dec: cumulative number of days in December with mean temperatures below 0°C (32°F); Freeze_Feb: cumulative number of days in February with mean temperatures below 0°C (32°F); Preci_Jun: precipitation in June

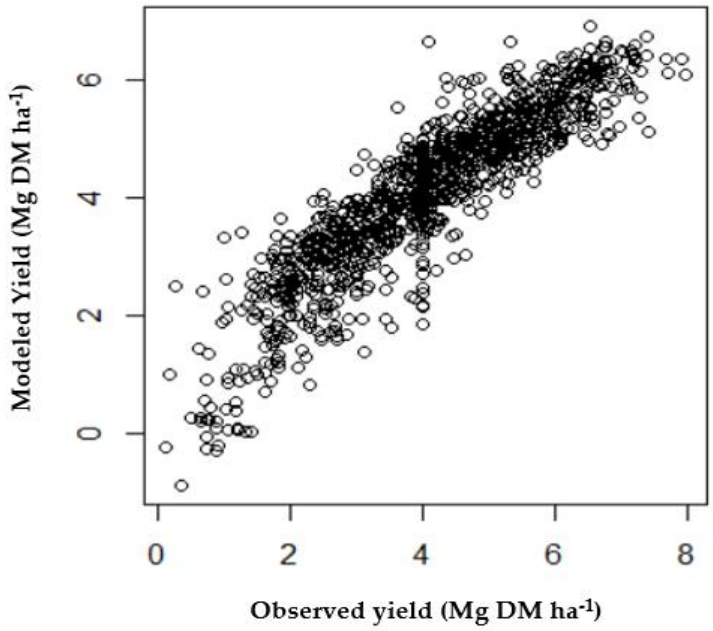

Figure S1: Modeled vs observed 1:1 scatter plots of the LMM

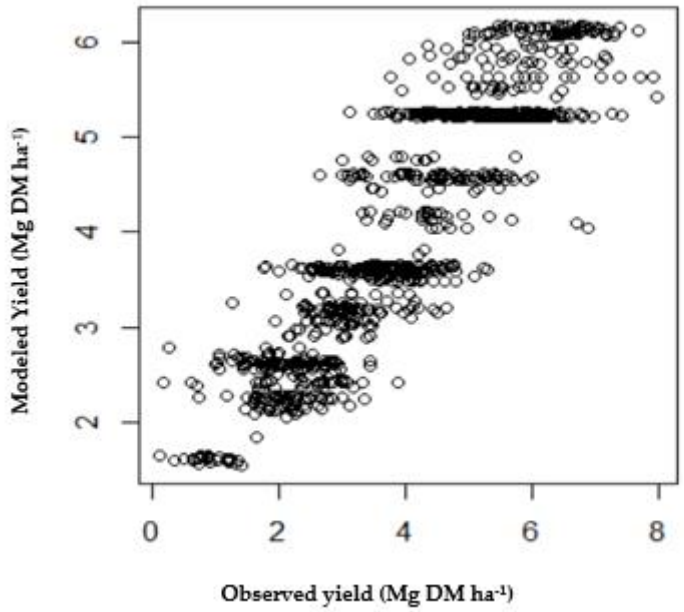

Figure S2: Modeled vs observed 1:1 scatter plots of the M5P

EQ 1. Equations for the evaluation metrics are given as:

1.1 Equation of coefficient of determination (R^2) is given as:

$$R^2 = 1 - \frac{\sum(\bar{y} - \hat{y})^2}{\sum(\bar{y} - \hat{y})^2} \quad \text{(Es1)}$$

1.2 Equation of root mean square error (RMSE)

$$RMSE = \sqrt{MSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\bar{y} - \hat{y})^2} \quad \text{(Es2)}$$

1.3 Equation of mean absolute error (MAE)

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|\bar{y} - \hat{y}| \quad \text{(Es3)}$$

Where, $\hat{y}$ = predicted value of y

$\bar{y}$ = mean value of y