

Phosphorus and Nitrogen Yield Response Models for Dynamic Bio-

Economic Optimization – An Empirical Approach

Supplemental material

S1: Analytical data

The data used for estimation of the response models is presented in Supplemental Tables S1-S6. The datasets used for model validation are presented in Supplemental Tables S7-S8. Notice that the observations associated with the same STP level or yield without added N come from the same experiment.

Table S1. Dataset for the first model element for coarse soils[†]

STP (mg l ⁻¹) ^{††}	Yield without added P (kg ha ⁻¹)	Weight (the number of the experiment years)
7	2100	10
8	3800	6
4.801	1850	4
8.501	2600	4
3.701	3300	4
4	2400	4
5	2600	7
5.501	1800	3
15	3700	16
12.101	5000	6
30	2600	8
21.901	4900	5
49.8	6000	3
9.6	4189	16
3	1893	15
23.5	2507	12
4.7	1730	16
6.9	1853	12
8.6	4401	9
41.1	4209	12
10.2	3645	18
3.9	3070	12
8.4	3951	9

[†] n=18, Source: Valkama et al. 2011 and Saarela et al. 1995, mean yield without added P=3222 kg ha⁻¹, mean STP at the beginning of the experiment=12.83 mg l⁻¹, range of the yields without added P is 1730-6000 kg ha⁻¹ and the range of the STP levels is 3-49.8 mg l⁻¹.

^{††} STP was measured at the beginning of experiments from the control (without added P).

Table S2. Dataset for the second model element for coarse soils. STP was measured at the beginning of experiments from the control (without added P)[†]

P fertilization (kg ha ⁻¹)	STP (mg l ⁻¹) ^{††}	Yield response (%)	Weight
--	---	--------------------	--------

0	7	0	10
15	7	16	10
30	7	25	10
45	7	27	10
60	7	31	10
0	8	0	6
15	8	5	6
30	8	6	6
45	8	14	6
60	8	11	6
0	4.8	0	4
36	4.8	21	4
0	8.5	0	4
15	8.5	18	4
30	8.5	28	4
45	8.5	31	5
60	8.5	30	5
0	3.7	0	4
15	3.7	8	4
30	3.7	8	4
45	3.7	6	4
60	3.7	9	4
0	4	0	4
15	4	16	4
30	4	20	4
45	4	22	4
60	4	14	4
0	5	0	7
15	5	21	7
30	5	27	7
45	5	29	7
60	5	31	7
0	5.5	0	3
36	5.5	21	3
72	5.5	40	3
0	15	0	16
15	15	5	16
30	15	6	16
45	15	8	16
60	15	6	16
0	12.1	0	6
6	12.1	-6	6
8	12.1	-1	6
10	12.1	-3	6
13	12.1	-6	6
15	12.1	-2	6

20	12.1	-7	6
25	12.1	0.5	6
35	12.1	11	6
0	30	0	8
15	30	4	8
30	30	6	8
45	30	6	8
60	30	7	8
0	21.9	0	5
8	21.9	-1	5
13	21.9	2.5	5
15	21.9	6	5
25	21.9	-1	5
35	21.9	3	5
0	49.8	0	3
8	49.8	-5	3
13	49.8	-4	3
15	49.8	-5	3
25	49.8	-7	3
35	49.8	-1	3

[†] n=66, Source: Valkama et al. 2011, mean P response=8.4%, mean STP at the beginning of the experiment=14.72 mg l⁻¹, mean P fertilization rate=25.27 kg ha⁻¹, range of the P responses is -7 to 40%, the range of the STP levels is 3.7-49.8 mg l⁻¹, and the range of the P fertilization rates is 0-72 kg ha⁻¹.

^{††} STP was measured at the beginning of experiments from the control (without added P).

Table S3. Dataset for the third model element for coarse soils[†]

N fertilization (kg ha ⁻¹)	Yield without added N (kg ha ⁻¹)	Yield response (%)	Weight
54	1300	89	2
108	1300	115	2
54	1500	75	2
108	1500	106	2
26	1000	36	3
52	1000	60	3
27	1000	20	2
54	1000	48	2
54	1610	71	2
108	1610	85	2
54	1400	84	3
108	1400	97	3
40	1680	79	4
54	1700	61	2
108	1700	89	2
54	1900	54	2
108	1900	72	2
54	2800	22	2
54	2000	45	3
108	2000	64	3
54	2080	51	3

108	2080	64	3
54	2700	48	5
108	2700	81	5
162	2700	86	5
216	2700	80	5
50	2800	43	3
75	2800	58	3
100	2800	64	3
125	2800	77	3
150	2800	72	3
80	2400	51	3
50	2500	69	2
50	2400	36	2
108	2400	37	2
50	2900	47	3
75	2900	66	3
100	2900	80	3
125	2900	80	3
150	2900	76	3
16	2400	26	6
32	2400	41	6
64	2400	59	6
128	2400	57	6
54	4000	13	2
108	4000	11	2
54	4500	5	2
108	4500	4	2
16	3200	14	3
32	3200	24	3
64	3200	22	3
26	3100	12	2
52	3100	25	2
103	3100	36	2
50	3500	10	2
100	3500	36	2
54	2100	55	5
108	2100	83	5
54	2120	61	5
108	2120	86	5
27	3940	10	4
54	3940	13	4
108	3940	16	4

18 [†] n=63, Source: Valkama et al. 2013, mean N response=53%, mean yield without added N=2496 kg ha⁻¹, mean N fertilization rate=77.73 kg ha⁻¹, range
 19 of the N responses is 4%-115%, the range of the yields without added N is 1000-4500 kg ha⁻¹, and the range of the N fertilization rates is 16-216 kg ha⁻¹.
 20

21 **Table S4.** Dataset for the first model element for clay soils[†]

STP (mg l ⁻¹) ^{††}	Yield without added P (kg ha ⁻¹)	Weight
0.8	3970	3
4	3300	6
5	2000	3
2.7	3500	4
5.9	3800	5
6.4	4700	5
40	4200	5
20.5	4300	5
10	3200	6
2.8	3304	18
5.3	3068	12
11.3	2905	12
43.7	4571	15
50.5	4565	15
7.2	3777	18
3.5	3391	12
8.5	3333	11
4.6	4749	15

22 [†] n=18, Source: Valkama et al. 2011 and Saarela et al. 1995, mean yield without added P=3700 kg ha⁻¹, mean STP at the beginning of the experiment
 23 =12.93 mg l⁻¹, range of the yields without added P is 2000-4749 kg ha⁻¹, and the range of the STP levels is 0.8-50.5 mg l⁻¹.
 24 ^{††} STP was measured at the beginning of experiments from the control (without added P).

25 **Table S5.** Dataset for the second model element for clay soils[†]

P fertilization (kg ha ⁻¹)	STP (mg l ⁻¹) ^{††}	Yield response (%)	Weight
0	0.8	0	3
6	0.8	7	3
25	0.8	6	3
50	0.8	14	3
100	0.8	16	3
0	4	0	6
15	4	10	6
30	4	6	6
45	4	17	6
60	4	19	6
0	5	0	3
18	5	5	3
0	2.7	0	4
18	2.7	8	4
36	2.7	13	4
0	5.9	0	5
8	5.9	1	5
13	5.9	6	5

15	5.9	7	5
25	5.9	3	5
35	5.9	2	5
0	6.4	0	5
8	6.4	1	5
13	6.4	1	5
15	6.4	17	5
25	6.4	4	5
35	6.4	17	5
0	40	0	5
15	40	0	5
30	40	2	5
45	40	2	5
60	40	-1	5
0	20.5	0	5
8	20.5	1	5
13	20.5	-3	5
25	20.5	-4	5
35	20.5	8	5
0	10	0	6
15	10	1	6
30	10	3	6
45	10	-0.6	6
60	10	4.7	6

[†] n=42, Source: Valkama et al. 2011, mean P response=4.6%, mean STP at the beginning of the experiment =11.15 mg l⁻¹, mean P fertilization rate=23.24 kg ha⁻¹, range of the P responses is -4% to 19%, the range of the STP levels is 0.8-40 mg l⁻¹, and the range of the P fertilization rates is 0-100 kg ha⁻¹.

^{††} STP was measured at the beginning of experiments from the control (without added P).

Table S6. Dataset for the third model element for clay soils[†]

N fertilization (kg ha ⁻¹)	Yield without added N (kg ha ⁻¹)	Yield response (%)	Weight
50	1800	57	2
75	1800	88	2
100	1800	106	2
125	1800	107	2
150	1800	108	2
54	1700	43	2
108	1700	59	2
54	1900	45	2
50	2800	22	3
75	2800	27	3
100	2800	21	3
125	2800	31	3
150	2800	23	3
50	2450	59	6
75	2450	85	6
100	2450	103	6

125	2450	102	6
150	2450	106	6
30	2200	53	4
60	2200	94	4
90	2200	120	4
120	2200	143	4
150	2200	160	4
180	2200	170	4
90	2800	61	3
90	3000	59	3
48	2000	17	1
50	2100	47	3
75	2100	87	3
100	2100	105	3
125	2100	116	3
150	2100	123	3
16	2400	26	6
32	2400	41	6
64	2400	59	6
128	2400	57	6
50	2400	14	2
75	2400	29	2
100	2400	41	2
125	2400	58	2
150	2400	57	2
48	2200	25	1
30	3200	20	3
60	3200	47	3
40	3900	19	4
80	3900	24	4
120	3900	23	4
40	3360	29	4
80	3360	35	4
120	3360	34	4

[†]n=50, Source: Valkama et al. 2013, mean N response=74%, mean yield without added N=2279 kg ha⁻¹, mean N fertilization rate=95.11 kg ha⁻¹, range of the N responses is 14%-170%, the range of the yields without added N is 1700-3900 kg ha⁻¹, and the range of the N fertilization rates is 36-180 kg ha⁻¹.

Table S7. Validation dataset for coarse soils[†]

N fertilization (kg ha ⁻¹)	P fertilization (kg ha ⁻¹)	STP (mg l ⁻¹) ^{††}	Yield (kg ha ⁻¹)	weight
0	0	13	1223	3
50	13	13	2987	3
100	26	13	3810	3
0	0	22	1978	5
50	9	22	3162	5
100	18	22	4238	5
80	17	19	3509	2

160	34	19	3559	2
0	0	21	2893	4
60	13	21	4140	4
80	17	21	4350	4
100	22	21	4388	4
120	26	21	4570	4
140	31	21	4628	4
160	35	21	4568	4
0	0	21	2396	5
48	9	21	3338	5
64	12	21	3452	5
80	15	21	3618	5
96	18	21	4195	5
65	14	21	4070	5
78	17	21	4118	5
80	12	7	3605	1
80	7	7	3630	1
81	11	7	3465	1
80	6	7	3720	1
80	7	7	3675	1
130	20	7	4065	1
130	11	7	3945	1
130	17	7	3885	1
130	9	7	3905	1
45	12	8	4350	1
90	24	8	4850	1
50	36	4	2300	1
101	73	4	3670	1

[†] n=35, Source: This study, mean N fertilization rate=81.04 kg ha⁻¹, mean P fertilization rate=16.91 kg ha⁻¹, mean STP at the beginning of the experiment=14.63 mg l⁻¹, mean yield=3664 kg ha⁻¹, range of the N fertilization is 0-160 kg ha⁻¹, range of the P fertilization is 0-73 kg ha⁻¹, range of the STP is 3.9-21.6 mg l⁻¹, and range of the yield is 1223-4850 kg ha⁻¹.

^{††} STP was measured at the beginning of experiments from the control (without added P).

Table S8. Validation dataset for clay soils[†]

N fertilization (kg ha ⁻¹)	P fertilization (kg ha ⁻¹)	STP (mg l ⁻¹) ^{††}	Yield (kg ha ⁻¹)	Weight
0	0	4	940	3
100	13	4	3107	3
100	9	4	3200	3
100	19	4	3083	3
99	19	4	3330	3
172	0	4	2783	3
0	0	9	1410	1
100	13	9	4170	1
100	9	9	4560	1
100	19	9	4420	1
99	19	9	4420	1
172	0	9	4470	1

0	0	10	1015	3
100	13	10	3165	3
100	9	10	3340	3
100	19	10	3430	3
99	19	10	3315	3
172	0	10	3035	3
0	0	18	894	10
50	11	18	2970	10
100	22	18	4159	10
150	33	18	4892	10
200	44	18	5194	10
0	0	12	1231	10
50	11	12	2927	10
100	22	12	3693	10
150	33	12	4182	10
200	44	12	4316	10
53	10	8	2380	6
88	17	8	3147	6
158	30	8	3435	6
48	9	12	2695	6
72	14	12	3427	6
96	18	12	3410	6
0	0	8	1713	2
104	24	8	3595	2
104	23	8	3825	2
105	46	8	3800	2
105	76	8	3785	2
60	13	31	4908	1
120	26	31	4843	1
53	23	20	3740	1
105	46	20	4030	1
150	65	20	3680	1
60	11	17	1884	7
120	23	17	2000	7
50	13	24	3958	2
101	26	24	4348	2
150	39	24	4256	2
80	17	17	4158	2
160	35	17	4203	2
0	0	5	1709	3
50	37	5	2774	3
101	73	5	3429	3
150	109	5	3707	3
0	0	3	2812	3
90	52	3	4508	3
180	105	3	4575	3

60	44	11	4007	3
120	87	11	4421	3
60	44	11	2220	1
120	87	11	2600	1
40	23	11	2100	1
80	47	11	3377	1
0	0	8	1833	3
100	58	8	3504	3
75	44	9	1846	10
150	87	9	2591	10

[†] n=68, Source: This study, mean N fertilization rate=91.62 kg ha⁻¹, mean P fertilization rate=27.98 kg ha⁻¹, mean STP at the beginning of the experiment =11.54 mg l⁻¹, mean yield=3307 kg ha⁻¹, range of the N fertilization is 0-200 kg ha⁻¹, range of the P fertilization is 0-109 kg ha⁻¹, range of the STP is 3.2-31.2 mg l⁻¹, and range of the yield is 894-5194 kg ha⁻¹.

^{**} STP was measured at the beginning of experiments from the control (without added P).

References

- Saarela I., A. Järvi, H. Hakkola, and K. Rinne. 1995. Fosforilannoituksen porraskokeet 1977 – 1994. Vuosittain annetun fosforimäärän vaikutus maan viljavuuteen ja peltokasvien satoon monivuotisisa kenttäkokeissa. MAATALOUDEN TUTKIMUSKESKUS TIEDOTE 16/95
- Valkama, E., R. Uusitalo, and E. Turtola. 2011. Yield response models to phosphorus application: A research synthesis of Finnish field trials to optimize fertilizer P use of cereals. *Nutrient Cycling in Agroecosystems* 91: 1-15
- Valkama, E., T. Salo, and M. Esala. 2013. Nitrogen balances and yields of spring cereals as affected by nitrogen fertilization in northern conditions: A meta-analysis. *Agriculture, Ecosystems and Environment* 164: 1–13