https://doi.org/10.17221/308/2025-PSE

Correlation of DGT-P and conventional soil P tests with rye shoot biomass and P uptake across temperate soils with differential soil properties

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Citation: Golestanifard A., Puschenreiter M., Manglberger R., Gotthard M., Eigner H., Spangl B., Wenzel W., Santner J. (2025): Correlation of DGT-P and conventional soil P tests with rye shoot biomass and P uptake across temperate soils with differential soil properties. Plant Soil Environ., 71.

Abstract: Several phosphorus (P) extraction tests are being used as soil P tests, but many studies have shown that the correlation of extractable P with plant yield and P uptake varies and sometimes is poor. Infinite sink extraction methods may be superior in estimating plant P availability. Soil P tests were evaluated for their power in determining plant-available P pools. Thirty arable soils covering different soil groups were tested for soil characteristics and extractable P pools. Rye was grown on these soils for six weeks and analysed for shoot yield and shoot P concentrations. Correlations between soil P concentrations, shoot yield and shoot P content were investigated. Extractable P pools mostly significantly correlated with soil pH, texture and amorphous iron oxide content. High and significant correlations were found among most of the extractable soil P pools, except for calcium acetate lactate (CAL)-extractable P. In contrast to previous studies, diffusive gradients in thin films (DGT)-extractable P employed in our pot experiment did not perform better than other extraction methods in correlating with plant available P and uptake, likely because water availability was not a limiting factor of P diffusion. Plant-available P in the soils investigated in this study was controlled by P quantity (i.e. the amount of adsorbed P) and P intensity (i.e. the soil solution P). We conclude that the advantage of infinite sink extraction methods over equilibrium-based techniques becomes less apparent if P is not strongly intensity-controlled and water availability is not a limiting factor of P diffusion.

Keywords: phosphorus; macronutrient; extractability; soil extraction; bioavailability; plant biomass; Mitscherlich function

Phosphorus (P) is a major nutrient for plants. In crop production systems, reliable data on soil P availability to crops is crucial for the achievement of optimal yields (Recena et al. 2022). The determination of a soil's P status by a soil P test is considered as the first and most important step for any fertilisation strategy. Soil P test results in the next steps are used to assess potential P deficits (based on a P test calibration) and calculate crop-specific fertiliser recommendations (Jordan-Meille et al. 2012).

Most soil P tests can be classified as quantity or intensity tests, with the extraction technique typically aiming at establishing a (quasi-)equilibrium during the extraction period. P intensity (I) is related to the concentration of P in soil solution, whereas P quantity (Q) represents the amount of soil P that buffers soil

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https://doi.org/10.17221/308/2025-PSE

solution P (Becket and White 1964, Peaslee and Phillips 1981). Several P extraction tests have been adopted as (national) standard extraction methods (Jordan-Meille et al. 2012). However, many studies have shown that the correlation of plant yields with extractable P concentrations varies and is sometimes poor (Mason et al. 2010, Recena et al. 2015), which may pose the risks of either insufficient or excessive fertilisation when determining fertiliser demand (Recena et al. 2022).

In recent years, novel P tests have been developed, some of which showed better performance than traditional quantity and intensity tests. Infinite sink extraction methods such as diffusive gradients in thin films (DGT) are desorption-based approaches, which were found to provide a more accurate assessment of P bioavailability than conventional extraction methods based on chemical equilibria (Degryse et al. 2009, Six et al. 2012, Santner et al. 2015, Wenzel et al. 2022). The DGT technique is a mechanistic surrogate of plant root P uptake, which is limited by the P diffusion rate. Furthermore, soil P depletion triggers P resupply (desorption and dissolution) from the soil solid phase. With the integration of P resupply and diffusion (Degryse et al. 2009, Santner et al. 2012, Menezes-Blackburn et al. 2016), DGT is able to assess both P quantity and intensity. Indeed, Menezes-Blackburn et al. (2016), using modelling and experimental evidence, showed that only one hour after deployment, DGT measurements are a function of solid-phase P resupply capacity, and concluded that differences in both P diffusion and resupply from the solid phase can be sampled by DGT.

The DGT method holds great promise for improving the correlation of soil P status with plant P concentration and yield (Degryse et al. 2009, Wenzel et al. 2022). Although it was introduced for assessing bioavailable soil P 20 years ago (Menzies et al. 2005), its performance compared to conventional soil P tests and the influence of soil characteristics on this performance is still insufficiently investigated, and the available data are partly conflicting. Some studies, which have been conducted in the tropical and subtropical zones with highly P-fixing soils, showed that DGT-P correlated better with P concentration and yields of wheat (Mason et al. 2010, Speirs et al. 2013), maize (Six et al. 2012), and tomato (Menzies et al. 2005) as compared to conventional quantity and intensity tests. However, DGT-P was no superior predictor for upland rice yield (Six et al. 2013) and pastures (Burkitt et al. 2016). Similarly, a few studies still have somewhat confounding data from pot and field trials on less developed European soils with less strong P retention or lower P buffer capacity (PBC). While in a pot trial, DGT-P correlated well with P uptake by rye (Duboc et al. 2017), Mundus et al. (2017) observed inconsistent results from pot and field trials at different plant growth stages. Moreover, using field trials, DGT-P correlated better with P uptake and plant biomass (wheat biomass, Wenzel et al. 2022; barley and wheat grain yield, Hill et al. 2021) as compared to equilibrium-based P tests. Nawara et al. (2017), analysing soil samples of several long-term P fertilisation trials in Europe, reported that the DGT test did not outperform conventional equilibrium-based soil extractions. They suggested that in young European soils, P is less strongly adsorbed compared to highly weathered tropical and sub-tropical soils with high P fixation potential and larger PBC, which implies that P availability in European soil types is controlled by the size of P pools in soils rather than by diffusional resupply of adsorbed P pools. Some of these contradictory results might be due to the further modification of soil P availability to crops by climate conditions (especially soil water status), plant P requirements and rhizosphere processes, which cannot be assessed by any soil P test (Hill et al. 2021).

The extraction power of different soil P tests might also be affected by soil physical and chemical properties to varying extents. While some studies investigated a few selected P extraction techniques, a more comprehensive, comparative assessment of DGT-P with a wide range of conventional soil P tests is still lacking. In contrast to many other studies, we compared P tests in controlled conditions across a wide range of WRB soil groups representative of large European areas. Accordingly, we compared the performance of the P tests in soils that vary considerably in terms of their control of P availability. By conducting the experiment in controlled conditions, we eliminated confounding factors such as climate and weather conditions, which often pose a problem for interpretation. Therefore, the aim of this study was to investigate a significant number of conventional soil P tests and the DGT method using a pot trial growing rye (*Secale cereale* L.) in a large set of 30 arable soils and determine the correlation of soil test P with shoot yield and P uptake. In this context, our study addresses the following research questions: (*i*) How does DGT-P compare to P-extractability by conventional soil tests?; (*ii*) What is the relation between soil characteristics and the extractability of P by the different soil P-tests?, and (*iii*) how well do the evaluated soil P tests correlate

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with shoot biomass and P uptake in an early growth stage of rye?

MATERIAL AND METHODS

Soil samples. Composite soil samples (0–20 cm) were collected from 30 selected Austrian arable soils covering a range of soil types representing arable soils in central Europe including Chernozems, Phaeozems, Cambisols, Fluvisols, Stagnosols, and Regosols and covering the typical range of soil physicochemical characteristics acting as main controls of P solubility (e.g., pH, lime content, oxide content). The soils were air-dried and passed through (*i*) a 4-mm sieve before setting up the pot experiment, and (*ii*) a 2-mm sieve prior to conducting soil analyses and soil P extraction.

General soil characteristics. All analyses were carried out in triplicate, except for total carbon (C) and nitrogen (N), as well as carbonate content, which were determined in duplicate. Texture was determined by the wet sieving and sedimentation method (Austrian Standards 2002). Soil pH was measured in 0.01 mol/L $CaCl_2$ (Austrian Standards 1999). The carbonate content was determined based on the emitted CO_2 after addition of 10% HCl (Austrian Standards 1999). Total nitrogen (N_t) and total carbon (TC) were determined by dry combustion (Austrian Standards 2013). Soil organic carbon (SOC) was calculated as the difference between TC and carbonate C. Exchangeable cations were analysed after 0.1 mol/L $BaCl_2$ extraction (1:20, *w*/*v*) (Austrian Standards 2000). Amorphous Fe- and Al-oxide fractions were determined in acid ammonium oxalate extracts (AAO-Fe, AAO-Al; Sparks 1996). Crystalline fractions of Fe- and Al-oxides were measured in sodium citrate-bicarbonate-dithionite (CBD-Fe, CBD-Al; Sparks 1996). P was also determined in both AAO and CBD extracts (AAO-P, CBD-P).

Determination of soil test phosphorus pools. We assessed soil P availability in this study using DGT and 9 other conventional P extraction methods, which included EUF (electro-ultrafiltration), $CaCl_2$ and porewater extractions as 3 P intensity tests, and CAL (calcium-acetate-lactate), AAO (acid ammonium oxalate), CBD (sodium citrate bicarbonate dithionate), Olsen, Mehlich 3, and *aqua regia* (near-total; referred to as total P throughout the text) extractions as 6 P quantity tests. An overview of the extraction methods and the analysis of the extracted P is given in Table 1. The tested methods were selected according to their main P extraction mechanism, such as anion exchange, ligand exchange, acid dissolution, cation (Al, Fe, and Ca) complexation and mineral co-dissolution (Jordan-Meille et al. 2012). The extracted P was determined colourimetrically using the molybdate blue method or ICP-OES (Perkin Elmer Optima 8300, Waltham, USA).

Plant experiment. Rye (*Secale cereale* L.) seeds were germinated in wet paper in the dark at 22 °C for 48 h. Subsequently, 7 healthy germinated seeds were transplanted into pots (15 cm high, 10 cm diameter) containing 1 kg air-dried, 4-mm sieved soil and corrected by the corresponding water content or dry weight factor. 24 h before transplanting, the soil was equilibrated with a nutrient solution (modified from Middleton and Toxopeus (1973) containing 4 g/L NH_4NO_3, 1.47 g/L K_2SO_4 anhydr., 444 mg/L $MgSO_4$ 7 H_2O, 360 mg/L $CaCO_3$ anhydr., 7.2 mL/L 1 mol/L HCl (to solubilise $CaCO_3$), 600 µg/L H_3BO_3, 158 µg/L $CuCl_2$, 5.5 mg/L $MnCl_2$ 4 H_2O, 80 µg/L $(NH_4)Mo_7O_{24}$ 4 H_2O, 300 µg/L $ZnCl_2$ and 2.4 mg/L Fe EDDHA (ethylenediamine-N,N'-bis(2-hydroxyphenylacetic acid). The nutrient solution had a pH of 6.3 and was applied weekly (except the week before harvest) to ensure that plants were supplied with all nutrients except P. This resulted in a total addition of 420 mg N, 198 mg K, 98 mg S, 43 mg Ca, 13 mg Mg, 31 µg B, 22 µg Cu, 458 µg Mn, 14 µg Mo, 43 µg Zn and 41 µg Fe per kg soil over the course of the experiment. Throughout the experiment, pots were monitored daily, and water was added when necessary to keep the water level close to the soil's maximum water holding capacity. Pot experiment was conducted in 4 replicates and plants were grown for 6 weeks in a growth chamber at 20 °C during the 14 h light period and at 15 °C during the 10 h nighttime. Furthermore, every pot was moved to a different position randomly once per week. At harvest, all plants were at the first tiller stage (BBCH 21), and 7 plants per pot were harvested. After harvesting, shoots were washed using deionised water and dried at 65 °C for 5 days after weighing, the biomass was homogenised and a subsample of 0.2 g was digested in a mixture of HNO_3 + H_2O_2 (8 mL + 2 mL) in a microwave (MARS 6, CEM, 20 min at 200 °C). After staining, the P concentration was measured on a photometer using the molybdate blue method.

Statistical analysis. Multiple linear regression analyses, between shoot yield, soil P tests, and soil variables were conducted using Excel (version 15.33, Redmond, USA). Linear correlation analysis was done using the

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Table 1. Overview of the soil phosphorus (P) test methods used in this study

Full name	Abbreviation	Extraction solution/ phase	Main extraction mechanism	Analysis of extracted P	Reference
Diffusive gradients in thin films	DGT-P	ZrOH-based binding gel	desorption enhancement	colourimetric	Wenzel et al. (2022)
Electro-ultrafiltration*	EUF-P	H_2O (de-ionised water)	desorption enhancement	ICP-OES	VDLUFA (2002)
Porewater concentration*	porewater-P	H_2O (de-ionised water), 24 h pre-incubation	soil solution P in equilibrium with adsorbed P	colourimetric	
$CaCl_2$ extraction*	$CaCl_2$-P	0.01 mol/L $CaCl_2$	desorption enhancement	colourimetric	Houba et al. (2000)
Calcium acetate lactate	CAL-P	0.3 mol/L CH_3COOH, 0.05 mol/L $C_6H_{10}CaO_6$ 5 H_2O, 0.05 mol/L $(CH_3COO)_2$ H_2O	anion exchange, acid dissolution	colourimetric	Austrian Standards (2019)
Sodium bicarbonate	Olsen-P	1 mol/L $NaHCO_3$; pH 8.5	cation complexation	colourimetric	Olsen et al. (1954)
Mehlich 3-P	Mehlich 3-P	0.2 mol/L CH_3COOH, 0.25 mol/L NH_4NO_3, 0.015 mol/L NH_4F, 0.013 mol/L HNO_3, 0.001 mol/L EDTA	acid dissolution, cation complexation	colourimetric	Mehlich (1984)
Acid ammonium oxalate in darkness	AAO-Al, AAO-Fe, AAO-P	0.175 mol/L $(NH_4)_2C_2O_4$ H_2O, 0.1 mol/L $H_2C_2O_4$, 1.0 mol/L $CH_3CO_2NH_4$	mineral dissolution	ICP-OES	Schwertmann (1964)
Sodium citrate-bicarbonate-dithionite	CBD-Al, CBD-Fe, CBD-P	0.3 mol/L $C_6H_5Na_3O_4$ $2H_2O$, 1.0 mol/L $NaHCO_3$, $Na_2S_2O_4$	mineral dissolution	ICP-OES	Mehra and Jackson (1960)
Aqua regia	–	HCl, HNO_3	mineral dissolution	ICP-OES	Austrian Standards (1999)

*Intensity tests (I). All other soil P tests are considered as quantity tests (Q), except DGT, which can sample both P intensity and quantity (Wenzel et al. 2022) and was determined by deploying saturated soil pastes corrplot package in R (R Development Core Team 2020). The performance of soil P tests was evaluated by assessing the goodness of fit (r^2, RMSEP, as root mean square error of prediction) of the data to the Mitscherlich Eq. using R:

$$y = a\,(1 - \exp^{bx}) \qquad (1)$$

where: y – rye biomass (g/pot) at soil P availability × (mg P/kg), and a and b are model parameters determined using a minimum sum of squares optimisation in Microsoft Excel.

RESULTS

Soil P concentrations and relation with soil characteristics. The selected wide variety of soils covered a broad range of P statuses and concentrations as well as of other soil characteristics like pH, clay content and cation exchange capacity (Tables 2 and 3). The amount of extracted P by different soil P tests depended on the methods' specific extraction strength and mechanism

Table2. Characteristics of the experimental soils

Soil	pH_{CaCl_2}	MWHC	SOC	N_t	C/N	$CaCO_3$ equivalent	Textural class	CEC ($mmol_c$/kg)	AAO-Al	AAO-Fe	CBD-Al	CBD-Fe
		(g/kg)				(g/kg)			(g/kg)			
1	7.44	435	21.2	1.78	11.9	76.0	CL	235	1.48	1.47	1.16	7.58
2	7.09	414	17.9	1.66	10.8	13.0	L	122	1.12	2.62	2.30	13.8
3	6.81	576	34.3	3.75	9.14	2.52	SiL	205	1.89	3.42	3.01	16.2
4	6.79	477	28.0	2.88	9.70	27.1	SiL	189	1.77	3.49	2.14	13.8
5	5.00	457	27.0	2.73	9.87	0.00	L	67.5	2.95	3.95	3.56	12.1
6	5.68	535	35.6	3.69	9.64	0.00	L	164	3.54	5.74	3.85	17.4
7	6.07	384	18.1	1.91	9.46	0.00	SL	130	1.34	4.72	2.02	16.4
8	5.73	460	15.7	1.45	10.8	0.00	L	90.1	0.96	7.90	1.24	17.7
9	6.38	482	25.0	2.18	11.5	0.00	L	163	1.18	5.27	1.33	14.3
10	5.68	418	24.9	2.36	10.5	0.00	L	89.0	2.46	5.44	2.85	13.0
11	6.13	366	15.7	1.66	9.48	0.00	SL	79.7	1.96	4.13	2.84	13.1
12	7.48	377	13.0	1.10	11.8	135	SiL	133	0.56	0.92	0.64	6.71
13	7.37	456	17.6	1.52	11.6	52.6	SiL	178	0.71	2.23	1.00	10.4
14	5.84	496	22.9	2.56	8.93	0.00	SiL	148	1.48	5.66	2.38	17.1
15	7.13	468	17.4	1.84	9.46	15.5	SCL	249	1.31	1.08	1.28	10.9
16	7.38	435	15.8	1.30	12.1	173	SiL	151	0.51	0.75	0.73	7.78
17	7.61	424	14.4	1.26	11.4	182	SiL	155	0.68	0.89	0.73	7.56
18	7.43	456	18.5	2.31	8.01	13.4	CL	241	1.15	1.76	0.87	6.47
19	7.63	358	19.6	1.73	11.3	202	L	183	1.39	0.94	0.78	6.82
20	7.62	360	13.7	1.10	12.4	252	L	163	1.22	0.91	0.68	5.65
21	7.61	391	30.6	1.81	16.9	209	L	194	1.21	0.88	0.75	5.99
22	7.56	386	19.5	1.43	13.6	215	SiL	171	1.21	0.94	0.73	6.14
23	7.45	414	13.4	1.25	10.7	44.6	SiL	178	1.04	1.01	1.01	9.27
24	7.41	422	22.2	1.02	21.7	115	SiL	131	0.67	1.12	1.00	9.22
25	7.44	461	16.0	1.60	10.0	63.7	SiL	173	0.90	1.69	1.13	10.9
26	6.89	435	29.4	3.11	9.44	14.3	C	413	1.90	5.61	1.68	16.3
27	6.34	512	24.8	2.59	9.59	0.00	SL	166	2.56	7.45	2.15	10.7
28	5.83	471	19.4	1.92	10.1	0.00	SL	121	2.07	5.66	2.03	11.5
29	6.34	459	18.5	1.79	10.3	0.00	L	110	1.21	5.76	1.21	11.3
30	5.31	348	16.1	1.58	10.2	0.00	SL	69.4	1.50	2.73	1.53	6.63

MWHC – maximum water holding capacity; SOC – soil organic carbon; N_t – total nitrogen; CEC – cation-exchange capacity; AAO-Al, AAO-Fe – acid ammonium oxalate extractable Al and Fe; CBD-Al, CBD-Fe – sodium citrate-bicarbonate extractable Al and Fe

https://doi.org/10.17221/308/2025-PSE

Table 3. Extractable phosphorus (P), shoot biomass and shoot P uptake.

Soil	Pore-water-P*	DGT-P	$CaCl_2$-P	Olsen-P	Q/I**	Mehlich 3-P	CAL-P	EUF-P	CBD-P	AAO-P	*Aqua regia*-P	Shoot biomass	Shoot P conc.	Shoot P uptake (mg/pot)
	(μg/L)		(mg/kg)			(mg/kg)						(g/pot)		
1	115	66.6	0.45	30.1	66.4	41	61.4	20.2	103	433	870	0.38	1.61	0.23
2	104	61.1	0.42	26.9	64.0	26.6	42.8	20.4	381	321	770	0.96	2.55	2.34
3	125	69	0.54	27.2	50.1	55.5	45.1	20.4	532	603	1 120	1.08	2.65	3.10
4	82.5	50	0.32	21.3	67.3	35.2	37.1	20.0	414	582	1 160	0.83	2.21	1.52
5	56.6	22.5	0.19	14.1	73.2	82	20.3	8.02	702	794	1 100	0.92	1.78	1.49
6	194	126	1.17	41	35.0	169	79.1	30.6	1 077	1 360	1 150	1.08	3.77	4.37
7	884	310	1.71	52	30.5	235	110	60.8	1 049	858	1 660	1.17	4.39	5.95
8	263	138	0.92	32.7	35.5	51.3	49.7	30.2	709	841	1 690	0.91	4.34	3.61
9	902	312	1.71	114	66.9	262	284	80.8	1 020	1 260	2 090	1.17	3.94	5.42
10	605	233	1.68	58.1	34.6	182	101	50.5	1 440	1 440	1 620	1.14	3.64	4.75
11	198	122	1.2	52.4	43.8	143	80.8	40.9	1 070	984	1 380	1.19	3.69	5.20
12	45.2	24.4	0.18	6.1	32.9	28.7	94.7	30.5	21	311	960	0.61	1.43	0.52
13	112	45.9	0.34	12.6	36.9	24.6	90.0	30.1	273	331	1 170	0.79	1.68	1.05
14	642	182	2.23	41.4	18.6	100	75.5	40.9	1 100	951	1 380	0.86	3.26	2.38
15	13.7	5.94	0.11	3.11	28.0	42.3	43.1	11.0	206	343	810	0.19	1.55	0.06
16	21.8	11.2	0.12	4.86	41.4	6.89	37.0	10.2	60	262	750	0.35	1.11	0.13
17	33.3	9.9	0.07	4.21	57.3	5.84	21.1	9.99	–	247	690	0.45	1.29	0.26
18	23.8	12.3	0.15	4.86	32.8	24.6	78.7	20.6	107	326	750	0.48	1.4	0.32
19	25.2	12.3	0.14	4.53	32.0	12.9	47.7	10.7	135	473	750	0.37	1.27	0.17
20	338	122	0.86	32.4	37.9	107	127	30.9	152	568	970	0.88	2.24	1.72
21	654	179	2.93	53.1	18.1	171	184	40.0	240	636	1 130	0.83	3.3	2.24
22	189	75	0.54	14.6	26.9	92.7	151	40.1	223	635	1 120	0.86	2	1.46
23	192	91.2	0.47	18.8	40.2	47.1	153	30.9	280	378	1 090	0.81	2.13	1.39
24	13.9	7.14	0.16	4.27	26.3	17	39.5	10.3	96	239	910	0.48	1.25	0.29
25	32	18.2	0.17	8.7	51.5	21.4	45.2	20.7	250	339	960	0.85	1.73	1.23
26	244	79.2	0.49	31.3	63.4	30.1	51.2	40.0	449	696	1 180	0.96	2.41	2.23
27	177	73.6	0.57	37.4	65.5	123	63.2	31.0	1 060	1 510	3 270	0.89	3.35	2.65
28	479	142	1.23	46.2	37.4	184	74.0	40.7	1 100	1 260	2 370	0.97	2.94	2.78
29	111	41.1	0.46	16.2	34.9	61.2	22.4	10.8	646	560	1 040	0.72	1.93	1.01
30	480	136	1.12	38.4	34.4	258	62.1	30.3	688	928	1 680	1.11	3.53	4.311
Mean	245	92.6	0.8	28.4	42.8	88.0	79.1	30.3	537	682	1 300	0.8	2.5	2.1
Min	13.7	5.94	0.07	3.11	18.1	5.84	20.3	8.02	21	239	690	0.19	1.11	0.06
Max	902	312	2.93	114	73.2	262	284	80.8	1 440	1 510	3 270	1.19	4.39	5.95
Median	151	71.3	0.48	27.05	37.2	53.4	62.6	30.3	414	593	1 120	0.86	2.23	1.62
Std	256	82.8	0.699	23.2	15.5	76.6	55.2	10.7	408	376	547	0.273	1.00	1.72

*Through centrifugation, after overnight incubation of the saturated paste; DGT-P – diffusive gradients in thin films; $CaCl_2$-P – $CaCl_2$ extraction; Olsen-P – sodium bicarbonate; **Olsen-P/$CaCl_2$-P concentration ratio; Mehlich 3-P – Mehlich 3-P; CAL-P – calcium acetate lactate; EUF-P – electro-ultrafiltration; CBD-P – sodium citrate-bicarbonate-dithionite; AAO-P – acid ammonium oxalate

(Tables 1 and 2). P extractability was influenced by specific soil characteristics to different extents, in particular by pH, the content of amorphous Fe-oxides (AAO-Fe) and sand content (Figure 1A), which was observed for

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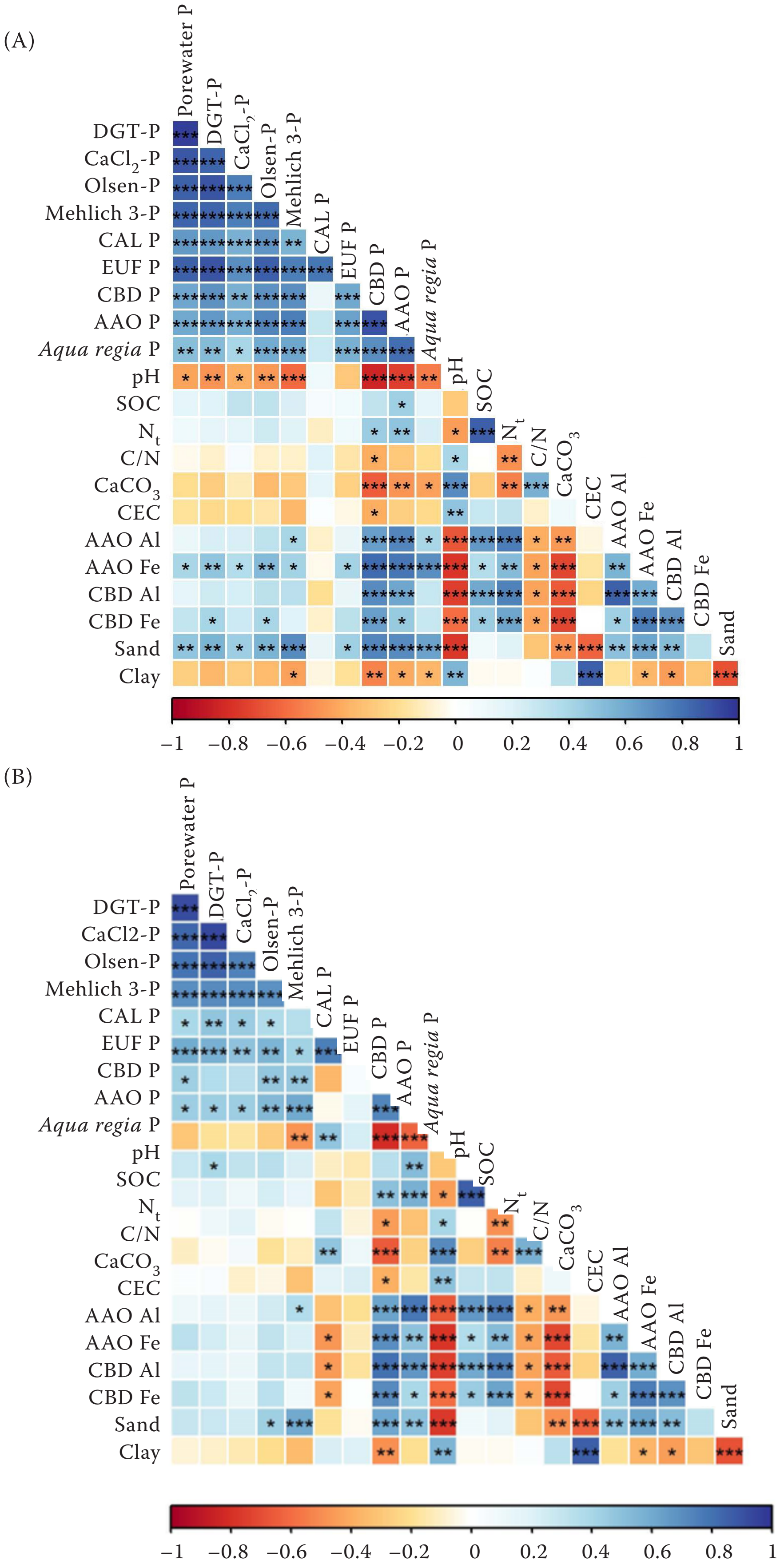

Figure 1. Correlation matrix showing a colour-coded representation of the correlation coefficient, *r*, for soil characteristics and (A) extractable soil phosporus (P) concentrations and (B) extractable soil P fractions. Significant correlations are indicated by stars (***$P < 0.001$; **$P < 0.01$; *$P < 0.05$). DGT-P – diffusive gradients in thin films; CaCl$_2$-P – CaCl$_2$ extraction; Olsen-P – sodium bicarbonate; Mehlich 3-P – Mehlich 3-P; CAL P – calcium acetate lactate; EUF P – electro-ultrafiltration; CBD P – sodium citrate-bicarbonate-dithionite; AAO P – acid ammonium oxalate; SOC – soil organic carbon; N$_t$ – total nitrogen; CEC – cation exchange capacity; AAO Al, AAO Fe – acid ammonium oxalate; CBD Al, CBD Fe – sodium citrate-bicarbonate-dithionite

Table 4. Soil phosphorus (P) fractions calculated as the ratio of extractable P pools to *aqua regia*-P

Soil	Pore-water-P	DGT-P	$CaCl_2$-P	Olsen-P	Mehlich 3-P	CAL-P	EUF-P	CBD-P	AAO-P
	(%)								
1	0.006	0.003	0.052	3.48	4.74	7.09	2.57	11.9	50.0
2	0.006	0.003	0.054	3.48	3.44	5.53	3.14	49.3	41.5
3	0.006	0.004	0.049	2.44	4.97	4.04	2.13	47.6	53.9
4	0.003	0.002	0.027	1.83	3.03	3.20	1.75	35.6	50.1
5	0.002	0.001	0.018	1.29	7.45	1.03	0.73	63.8	72.2
6	0.007	0.005	0.078	2.71	11.2	4.72	2.37	71.3	89.7
7	0.020	0.007	0.103	3.14	14.2	6.64	4.07	63.3	51.8
8	0.007	0.004	0.055	1.93	3.04	2.44	1.89	42.0	49.7
9	0.021	0.007	0.082	5.46	12.6	13.6	4.19	48.7	60.5
10	0.016	0.006	0.103	3.58	11.2	5.75	3.36	88.4	88.8
11	0.005	0.003	0.086	3.79	10.4	5.84	3.57	77.3	71.1
12	0.002	0.001	0.019	0.63	2.98	9.83	3.59	2.15	32.3
13	0.004	0.002	0.029	1.07	2.10	7.68	2.62	23.3	28.2
14	0.023	0.007	0.161	3.00	7.24	4.90	3.57	79.5	68.8
15	0.001	0.000	0.014	0.38	5.20	5.29	2.45	25.3	42.2
16	0.001	0.001	0.016	0.65	0.92	4.93	1.55	7.99	34.9
17	0.002	0.001	0.011	0.61	0.84	3.05	1.43	–	35.6
18	0.001	0.001	0.020	0.65	3.29	10.5	3.45	14.3	43.6
19	0.001	0.001	0.019	0.61	1.72	6.39	2.28	18.0	63.3
20	0.013	0.005	0.088	3.34	11.0	13.1	4.05	15.7	58.6
21	0.023	0.013	0.259	4.69	15.1	16.3	3.55	21.1	56.1
22	0.007	0.003	0.048	1.30	8.29	13.5	3.66	19.9	56.7
23	0.007	0.003	0.043	1.72	4.31	14.0	3.59	25.6	34.5
24	0.001	0.000	0.018	0.47	1.85	4.32	1.37	10.5	26.1
25	0.002	0.001	0.018	0.90	2.22	4.69	2.84	26.0	35.2
26	0.014	0.005	0.042	2.64	2.54	4.32	3.38	37.9	58.8
27	0.003	0.001	0.017	1.15	3.75	1.93	1.22	32.3	46.1
28	0.010	0.003	0.052	1.95	7.77	2.79	1.97	46.4	53.0
29	0.005	0.002	0.045	1.56	5.89	2.15	1.68	62.2	53.9
30	0.010	0.003	0.066	2.28	15.3	3.21	1.96	40.9	55.2
Mean	0.008	0.003	0.056	2.09	6.3	6.42	2.67	38.2	52.1
Min	0.001	0.000	0.011	0.38	0.8	1.03	0.73	2.2	26.1
Max	0.023	0.013	0.259	5.46	15.3	16.3	4.19	88.4	89.7
Median	0.006	0.003	0.047	1.88	4.9	5.11	2.59	35.6	52.4
Std	0.007	0.003	0.051	1.33	4.4	4.03	0.96	23.2	15.6

DGT-P – diffusive gradients in thin films; $CaCl_2$-P – CaCl2 extraction; Olsen-P – sodium bicarbonate; Mehlich 3-P – Mehlich 3-P; CAL P – calcium acetate lactate; EUF P – electro-ultrafiltration; CBD P – sodium citrate-bicarbonate-dithionite; AAO P – acid ammonium oxalate

both P intensity and P quantity tests, including *aqua regia*-P (total P). No or little influence on extractable soil P was found for soil carbon (including the organic and inorganic fraction) and the cation exchange capacity.

Soil P fractions (Table 3), calculated as the ratio of extractable P to total (*aqua regia*) P, did not correlate significantly with soil characteristics except for Mehlich 3-P, AAO-P, CBD-P and CAL-P fractions (Figure 1B).

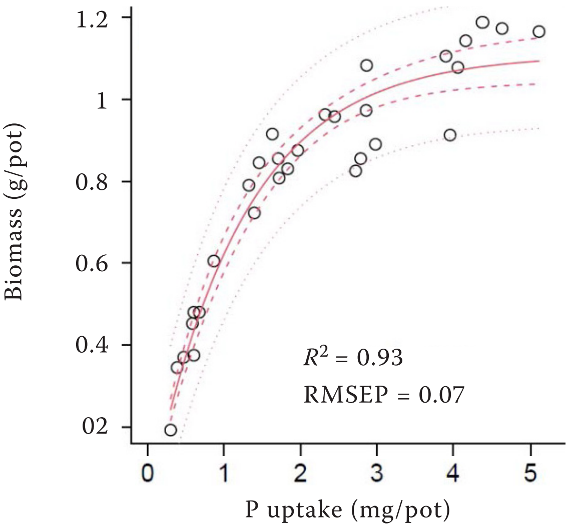

Figure 2. Rye shoot biomass as a function of phosphorus (P) uptake. The R^2-value corresponds to the linear fit between the observed and predicted shoot biomass. RMSEP is an indicator of the predicted root mean squared errors between the observed and predicted shoot biomass. The points are individual observations, and the solid lines represent the predicted shoot biomass based on the Mitscherlich model (Eq. 1). The dashed lines correspond to the 95% confidence bands, whereas the dotted lines represent the 95% forecast bands

Correlation between extractable P pools. The highest correlations ($r \geq 0.9$) were found between porewater-P and DGT-P ($r = 0.95$) and DGT-P and Olsen-P ($r = 0.9$) (Figure 1A). The correlation coefficients of DGT-P with $CaCl_2$-P, and Mehlich 3-P, and also EUF-P with Olsen-P and porewater-P were > 0.8. The correlations between conventional soil P tests had coefficients ranging from 0.7 to 0.9 and were all highly significant ($P \leq 0.001$). The lowest coefficients of correlation were found between CAL-P and the other soil P tests (r = 0.3–0.77). Total P correlated well with EUF-P, Olsen-P and Mehlich 3-P ($r \approx 0.6$), and had the highest correlation with AAO-P ($r = 0.85$).

For extractable P fractions, the highest coefficients of correlation were found between the DGT-P fraction, the $CaCl_2$-P fraction ($r = 0.94$) and the Olsen P fractions ($r = 0.82$), respectively (Figure 1B).

Correlation of P uptake and biomass production in rye. The plot of biomass *versus* shoots P uptake showed a good Mitscherlich fit to the data (Figure 2; $R^2 = 0.93$, RMSEP = 0.07). Additionally, multiple regression analysis indicated that only soil P availability, determined by different soil P tests (DGT-P, Table 5), was the limiting factor determining shoot biomass and P uptake.

Table 5. Multiple regression model explaining shoot phosphorus (P) uptake and shoot biomass by P availability (log_{10}-transformed DGT-P) and other soil characteristics

	Shoot P uptake			Shoot biomass		
	P-value	regression	ANOVA	*P*-value	Regression	ANOVA
Intercept	0.978			0.988		
pH_{CaCl_2}	0.503			0.924		
CEC	0.815			0.950		
AAO-Al	0.900			0.472		
AAO-Fe	0.592			0.775		
CBD-Al	0.940			0.257		
CBD-Fe	0.244			0.835		
Clay	0.775			0.980		
N_t	0.739			0.814		
SOC	0.940			0.732		
DGT-P	0.000			0.000		
Sand	0.233			0.812		
r^2		0.876			0.799	
Adjusted r^2		0.800			0.676	
Standard error		0.640			0.158	
Critical *F*-value			5.1×10^{-6}			2.6×10^{-4}
F-value			11.5			6.51

CEC – cation exchange capacity; AAO Al, AAO Fe – acid ammonium oxalate; CBD Al, CBD Fe – sodium citrate-bicarbonate-dithionite; N_t – total nitrogen; SOC – soil organic carbon; DGT-P – diffusive gradients in thin films

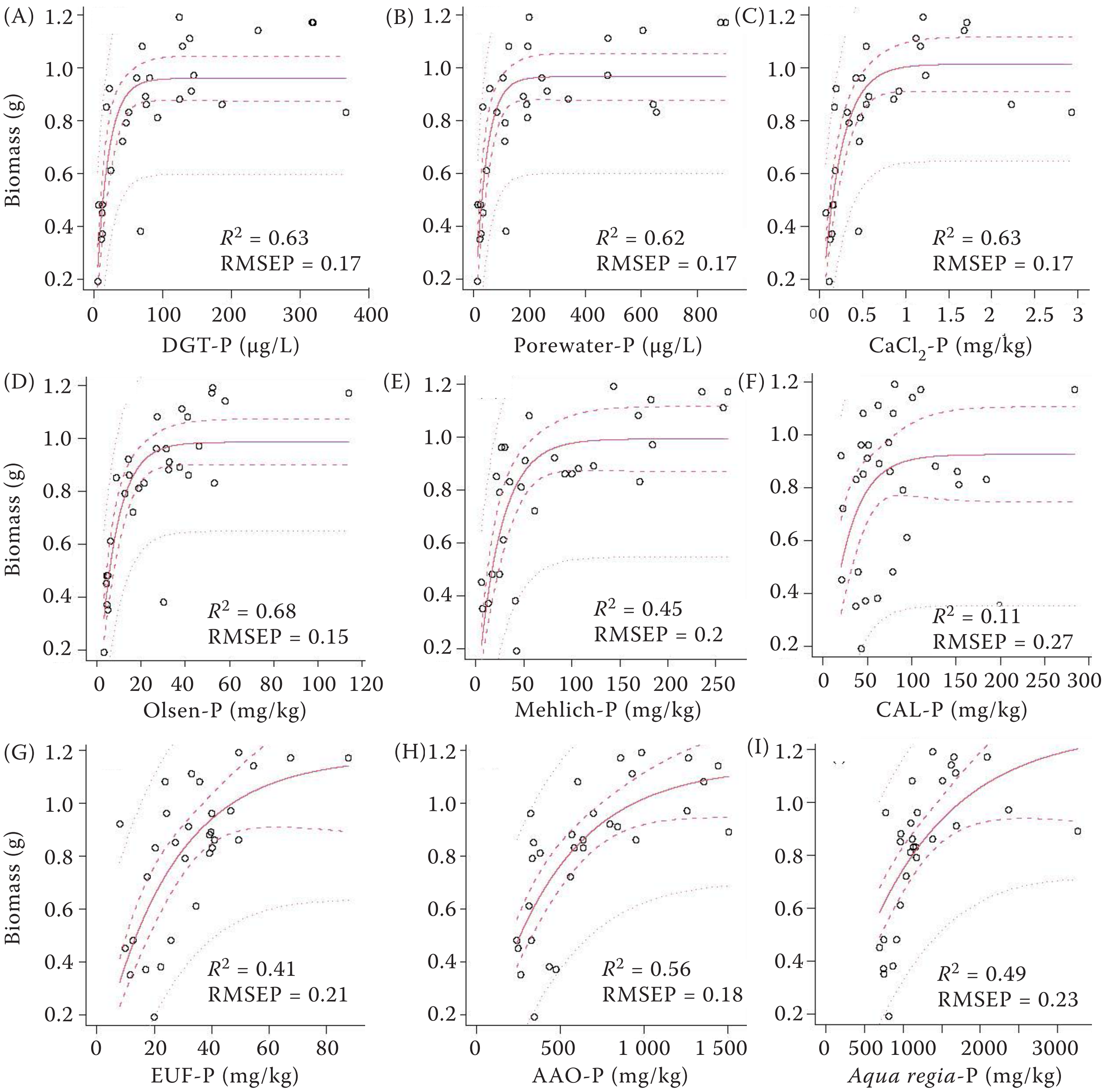

Figure 3. Rye shoot biomass as a function of extractable phosphorus (P). The R^2-values correspond to the linear fit between the observed and predicted shoot biomass. Additionally, the predicted root mean squared errors (RMSEPs) between the observed and predicted shoot biomass are given in each subplot for each soil P test. The points are individual observations, and the solid lines represent the predicted shoot biomass based on the Mitscherlich model (Eq. 1). The dashed lines correspond to the 95% confidence bands whereas the dotted lines represent the 95% forecast bands. DGT-P – diffusive gradients in thin films; CaCl$_2$-P – CaCl$_2$ extraction; Olsen-P – sodium bicarbonate; Mehlich 3-P – Mehlich 3-P; CAL P – calcium acetate lactate; EUF P – electro-ultrafiltration; AAO P – acid ammonium oxalate

Plant response to extractable soil P concentrations. Shoot biomass, shoot P concentrations and uptake are presented in Table 3. Fitting the rye biomass production *versus* the whole range of soil P concentrations using the Mitscherlich function (Figure 3) showed that DGT, intensity tests and several quantity tests had a comparable performance. The highest goodness of fit was found for DGT-P, CaCl$_2$-P, porewater-P Olsen-P and, AAO-P (R^2 = 0.56–0.68; RMSEP = 0.15–0.18) whereas the perfor-

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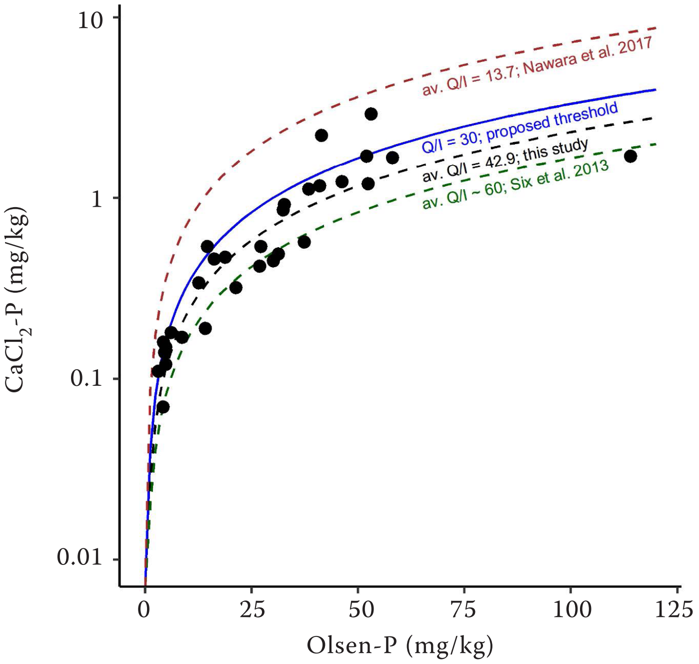

Figure 4. Q/I plot showing the relation between Olsen-P (representing P quantity, Q) and $CaCl_2$-P (representing intensity, I). Black circles represent individual soils of our study; the black line represents Q/I = 42.9, the average of the soils investigated in this study. The blue line represents Q/I = 30, which was suggested as a Q/I threshold below which P quantity and above which P intensity controls P resupply (Nawara et al. 2017). The brown and green lines represent Q/I = 13.7 and Q/I ~ 60, average values found for European soils in Nawara et al. (2017) and for African soils in Six et al. (2013), respectively

mance of total P, Mehlich 3-P and EUF-P was a bit lower (R^2 = 0.41–0.49; RMSE = 0.2–0.23). Poorer fit was observed for CAL-P (R^2 = 0.11, RMSEP = 0.27).

Phosphorous quantity and intensity ratio. The correlation between P intensity (represented by $CaCl_2$-P) and P quantity (represented by Olsen-P) is shown in Figure 4 as Q/I plot, following the approach by Nawara et al. (2017). The average Q/I ratio for all investigated soils in this study was 42.9 ± 15.9.

DISCUSSION

Soil P concentration as plant growth limiting factor. The current study was carried out on a large set of soils on a range of soil types representing arable soils in central Europe and covering the soil chemical characteristics acting as main controls of P solubility, based on the premise that available P is the only factor limiting plant growth. The large variation of the physico-chemical soil properties (Table 2) along with the relatively large number of soils, the completely randomised soil sampling design, and the clear Mitscherlich-type relationship between shoot P uptake and biomass (Figure 2) strongly suggest that soil P availability is the main plant growth limiting factor in our pot experiment. This is further substantiated by multiple regression analysis showing that shoot P uptake and biomass are largely driven by P availability (e.g., DGT-P) whereas none of the soil properties listed in Table 3 adds significant explanatory value (Table 3). Accordingly, we consider the biomass and P uptake responses of the rye plants to the soil P test results to be virtually unbiased by other potential growth-limiting factors. Therefore, the investigated soil P tests in this study can be evaluated for their predictive power of plant response to soil P availability. Soil P tests showing high correlation with plant biomass and/or crop yield are a prerequisite for a more accurate and appropriate calculation of P fertiliser needs and thus for achieving a more sustainable P fertiliser management (Recena et al. 2022).

Soil P concentrations determined by different extractants and methods. To indicate that to what extent the total P is plant available and related to soil properties, we calculated P fractions, however, correlation analysis showed that extractable P concentrations are more closely related to soil properties (Figure 1). Additionally, soil P concentrations could better predict shoot biomass (except for CAL-P; Figure 3) than of soil P fractions (data not shown).

Our data show that the different methods vary strongly in their extraction power, and are affected by soil physico-chemical properties to different degrees (Tables 1 and 3). The mean values of the extracted P concentrations in all 30 soils increased in the sequence DGT-P (92.6 µg/L; 5.94–312) < porewater-P (245 µg/L; 13.7–902 or 108 µg/kg; 5.9–435) < $CaCl_2$-P (0.8 mg/kg; 0.07–2.93) < EUF-P (30.3 mg/kg; 8.02–80.8 mg/kg) ~ Olsen-P (28.4 mg/kg; 3.11–114 mg/kg) < CAL-P (79.1 mg/kg; 29.3–284) < Mehlich 3-P (88.0 mg/kg; 5.84–262) < CBD-P (537 mg/kg; 21–1 440) < AAO-P

(682 mg/kg; 239–1 510) < *aqua regia*-P (1 300 mg/kg; 690–3 270). This order of extractability is in line with the observations of other researchers (Kulhánek et al. 2009, Wuenscher et al. 2015). Porewater extraction was done using centrifugation of saturated soils and hence involved varying soil:solution ratios (1:0.3–1:0.7; allowing the expression of porewater P as μg/L and μg/kg), which are related with different organic matter and clay contents and with varying mineralogy. Greater P extraction using 0.01 mol/L $CaCl_2$ with soil:solution ratio 1:10 compared to porewater centrifugation is expected, not only due to the larger buffer power which triggers dissolution of P precipitates and resupplies higher amounts of P into the liquid phase, but also because of Cl^- exchanging for P (Wuenscher et al. 2015). It should be mentioned that we deployed saturated soil pastes for DGT-P measurements and for this reason, we used zirconia-oxide gels to sample P instead of ferrihydrite gels to avoid iron reduction and subsequent decrease of sorption capacity of resin gel. According to the mean values of extracted P (Table 2), while DGT and intensity tests extracted much less than 1% of total P, some mild quantity tests extracted less than 7%, whereas AAO and CBD extracted more than 50% of total P. The intensity tests and the DGT-P concentrations show a larger variability (max:min > 10) than P quantity test (max:min < 10) and total P concentrations (max:min < 5) among the 30 studied soils (Table 3). Meanwhile, all used tests correlated well with each other as indicated in Figure 1. This is notable due to the different extractants with differing pH values and various degrees of pH buffering (Table 1). Good correlation between a number of soil P tests has also been observed in other studies (Wuenscher et al. 2015, Nawara et al. 2017). Nawara et al. (2017) observed that Olsen-P and AL-P (ammonium lactate and acetate; pH = 3.75) correlated well despite their strongly contrasting pH. It is also remarkable that the correlation coefficient between DGT, intensity and weaker quantity tests (e.g., Olsen-P) on the one hand and stronger quantity tests (e.g., *aqua regia*-P and AAO-P) on the other hand declines with increasing extraction power. A comparable observation was also found by Wuenscher et al. (2015) in the soil P test set evaluated by those authors, which did, however, not include DGT.

Shoot response to soil P concentrations. As shown in Figure 3, rye shoot biomass increased across the whole range of P concentrations determined by all P-tests (except CAL) with strongly varying extractability. In earlier studies, DGT-P showed better predictive power of plant biomass and plant P concentrations than equilibrium-based extraction approaches, in particular when soils with higher P fixation potential (larger PBC) such as strongly weathered tropical and subtropical soils were investigated (Menzies et al. 2005, Mason et al. 2010, Six et al. 2012, Speirs et al. 2013). We are aware of the different plant growth stage at harvest time in our pot experiment compared to the field experiments evaluated by Nawara et al. (2017) and other field studies. However, it should be noted that root activity and nutrient uptake generally diminishes at reproductive growth stage due to sink competition for carbohydrates so that the maximum nutrient uptake occurs at vegetative growth stage (Marschner 2012). Hence, internal remobilisation of nutrients during reproductive growth plays an important role so that biomass in vegetative growth stage acts as a proxy for final grain yield. Batten et al. (1986) demonstrated that up to 90% of the total P in wheat grains can be related to remobilisation of P compounds from vegetative organs.

In contrast, the results of our study show similar predictive power of DGT and several conventional equilibrium-based soil P tests. Nawara et al. (2017) compared the results of soil P tests using crop yields obtained from Central European long-term field experiments. They advocated that P quantity tests were superior to P intensity tests such as DGT-P and $CaCl_2$-P, based on the goodness of Mitscherlich fits. Our results, however, indicate that the DGT method performs as well as most of the conventional equilibrium-based approaches, such as Olsen-P (Q test), on soil types of the temperate climate in Central Europe. As already pointed out by Nawara et al. (2017), the better performance of DGT on highly weathered tropical soils in comparison to young post-glacial European soils is likely due to the less strong P binding (lower PBC) in European soil types, whereas in tropical soils P is strongly sorbed by Al and Fe-oxyhydroxides. In the latter, P supply control is dominated by diffusional resupply, whereas in central and northern European soil types, the resupply is mainly controlled by the P quantity in soil (Jordan-Meille et al. 2012, Nawara et al. 2017).

Our results show that the extracted P in all tests except CAL was significantly correlated with total soil P over the tested range of total soil P concentrations (Figure 1), confirming that P availability was largely determined by the quantity of P present in soil. Seed P contributes to shoots and roots P supply in the first days after seed germination (Marschner 2012). The P concentration in our rye seeds which was 2.76 mg P/g seed. Seven seeds weighed 0.168 g ± 0.008, their P content was therefore 0.467 mg P per pot. Pypers et al. (2006) estimated that 30% to 40% of the seed P reserve contributed to shoot P of maize and cowpea, respectively, under P-deficient conditions. Considering that the shoot P content on soil 15 was lowest with 0.060 mg/pot and root P content was not determined, it is apparent that seed P reserves have contributed to total plant P, in particular on low-P soils. Still, a clear response of the plants to soil P was determined especially on low-P soils, suggesting that the evaluation of plant response to varying soil P levels as determined by different tests was still a valid approach. Comparable goodness of fit (Figure 3) between soil P and plant biomass as obtained for intensity tests (e.g., $CaCl_2$ and porewater) as well as DGT and quantity tests (e.g., Olsen-P, AAO-P and even *aqua regia*-P) suggests that for the studied soils, the P availability to plants and the shoot biomass production was controlled by both diffusional resupply and the quantity of available P. This interpretation is further supported by the ratio of Q-P and I-P (expressed here as Olsen-P divided by $CaCl_2$-extractable P; Table 3). This Q/I ratio for all soils was on average 42.9 ± 15.9 and thus somewhat higher than the ratio of 30 (Figure 4), which was proposed by Nawara et al. (2017) as a separator between quantity- and intensity-controlled P supply. On the other hand, the average Q/I ratio of our study is below the average ratio of ~60 in the study of Six et al. (2013), who investigated a set of strongly P-sorbing African soils. It appears that the soils of our study are in the transition between Q and I-controlled soils. This explains why on the one hand high correlation coefficients (often > 0.8) between extractable P obtained with different methods were found, but also why both Q and I tests showed a comparable predictive power of plant P response to available soil P (Figures 1–3). The average Q/I ratio for all soils of Nawara et al. (2017) was 13.7 ± 6.4 and thus much lower than in our study, which is presumably due to the fact that several soils from freshly P-fertilised experimental plots were included in their study, whereas the soils investigated in our study included soils from fertilised and non-fertilised plots (soil 21 was never fertilised and soil 24 was not fertilised since 2000). Evaluating the results from our study and from Nawara et al. (2017) suggests that in well-fertilised temperate soils as investigated by Nawara et al. (2017) DGT-P has less predictive power than Olsen-P, whereas in temperate soils with different fertilisation levels (this study) the predictive power of DGT-P is of equal rank as Olsen-P. However, in highly weathered soils as investigated e.g., by Six et al. (2013) the predictive power of DGT-P is clearly superior to Olsen-P. On top of that, it should be further noted that in the study of Nawara et al. (2017) the DGT method was applied in an approach deviating from the standard method, which may limit the comparability with other studies, as pointed out by Santner et al. (2018). It should also be mentioned that we used ZrOH DGT gels to sample P instead of ferrihydrite gels to avoid iron reduction and hence diminishing the gel sorption capacity.

In contrast to some researchers (e.g., Six et al. 2013, Nawara et al. 2017) who referred to the DGT as intensity test, Wenzel et al. (2022) and Hill et al. (2021) argued that under P diffusion limitation, DGT mimics plant root P uptake and perturbs the P equilibrium at the solid-liquid interface, and hence samples the diffusive P supply in soil solution as well as P resupply from the solid phase. Wenzel et al. (2022) reported the performance of DGT-P, H_2O-P, and ammonium lactate-extractable P (AL-P) using archived soils and wheat biomass data obtained from a long-term field fertilisation experiment in weakly to moderately weathered soils in Sweden. In contrast to our findings, Wenzel et al. (2022) showed that DGT-P measurements outperformed conventional equilibrium-based P tests, especially, when they excluded the soils with distribution coefficients (Kd, defined as AL-P:DGT-P) ≥ 0.1 g/Lor soils with larger P buffer power. Better performance of DGT-P compared to other soil P tests may be expected in many conditions because not only does it mimic diffusion-controlled root P uptake (Degryse et al. 2009), but is also more sensitive to soil PBC and less affected by soil properties such as pH and ion concentrations than equilibrium-based batch extraction (Mason et al. 2010, Recena et al. 2015, Menezes-Blackburn et al. 2016, Hill et al. 2021). Six et al. (2012) found that in tropical soils with larger PBC, DGT can sample only the maize-accessible P pool. Similarly, Santner et al. (2015) demonstrated that maize roots and DGT access the same P pool in relatively little-developed European soils with low PBC. However, significant reduction in P desorption rate in extremely depleted soils and soils with long-term P accumulation and fixation may disturb the correlation between P sampled by standard DGT

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procedures (24 h extraction time) and P uptake of plants during the growth season, as reported by Wenzel et al. (2022).

Higher performance of DGT in weakly to moderately developed European soils compared to conventional extraction approaches, as observed by Wenzel et al. (2022), might to some extent also be explained by the differences between field- and our controlled pot conditions. In field conditions, plants may experience drought periods, limiting P supply by mass transport from the bulk soil towards the rhizosphere soil, probably making P intensity and diffusion control (as captured by DGT) more important. At limited water availability, narrower and steeper P depletion zones in the rhizosphere were observed by Gahoonia et al. (1994), explaining the importance of diffusion and mass flow in P transport and uptake. In our controlled pot experiment water supply was kept at a non-limiting level, making P (and other nutrients) generally more available for the plants. Therefore, we might expect different performance of P tests in field and greenhouse conditions, possibly levelling off differences between P tests based on different extraction mechanisms. By studying on 2 calcareous and 2 non-calcareous soils, the better performance of DGT-P than CAL-P in prediction of grain P content and wheat yield grown on soils of eastern Austria, with more sand and calcite contents and less precipitation (516 mm), compared to a more western location (696 mm), was observed by Hill et al. (2021). These authors attributed their observation to the diffusion-limited root P uptake and limited water availability in the rainfed soils of eastern Austria. It should be noted that all investigated soil samples by Nawara et al. (2017) had been collected from fields located in Belgium, England, France and Sweden, regions with relatively high average annual rainfall (674–1 038 mm). Duboc et al. (2017), observed equal performance of DGT-P and Olsen-P ($R^2 = 0.88$ for P uptake) in an evaluation of 13 P fertilisers and amendments in a pot experiment using rye and one non-calcareous low-P soil.

Among the standard soil P tests, poor predictability of biomass production and low correlation coefficients with other soil P tests were obtained for CAL-P (Figures 1 and 3), which is – along with EUF – a standard soil P test in Austria and Germany (VDLUFA 1991, Austrian Standards 2019). Our findings are in contrast to Wuenscher et al. (2015), who found correlations of $r > 0.8$ between CAL-P and other tests (Olsen-P and Bray II-P). Zbíral and Nemec (2002) reported that the relation of CAL-P with Mehlich 3-P was largely depending on the carbonate content in soils, ranging from $r = 0.38$ in all soils to $r = 0.74$ for carbonate-containing soils. The correlation coefficient of CAL-P with soil characteristics in our study was low and not significant, similar to Wuenscher et al. (2015). In general, the CAL extractant is problematic due to several and partly contrasting effects on soil chemistry, especially when considering calcareous *vs.* non-calcareous soils. Lower CAL-P extraction yields in non-calcareous soils might be attributed to the lower extraction pH and consequently diminishing P desorption from pH-dependent charge surfaces like oxides (Barrow 2017). However, lower extraction capacity of CAL solution in calcareous samples might to some extent be attributed to reduction in H^+ activity (increase of the initial pH of CAL solution from 4.1 up to 4.8; Schüller 1969) and consequently diminishing P extractability power. Additionally, the relatively high Ca concentration in CAL solution may decrease the solubility of Ca phosphate minerals (Schüller 1969). In contrast, calcite and associated P can be dissolved due to formation of H_2CO_3 (pK1 = 6.35) and subsequent removal of CO_2 (Lindsay 1979). We found that after exclusion of carbonate-containing soils, CAL-P could explain around 50% of biomass production in non-calcareous soils (data not shown). Likewise, Hill et al. (2021) observed a better performance of the CAL test on non-calcareous soils. Our data suggest that CAL is less suitable test for predicting biomass response to P availability compared to the other soil P tests evaluated in this study.

On the other hand, EUF (electro-ultrafiltration) performed moderately well among the other top-performing tests compared in this study (Figure 3). It should be noted that just with removing the most acidic soil 5 (Table 2), the goodness of fit (R^2) would increase to 0.57. The EUF approach was developed several decades ago, but seems to be one of the "forgotten methods", as it is hardly used in scientific or routine laboratories, except in the sugar industry in Austria and southern Germany. Steffens (1994) demonstrated in a 4-year pot experiment using different plants and 15 European Alfisol (topsoils) that plant P availability could be better explained by EUF when compared to CAL, double lactate, Mehlich 3 or water extraction based on the calculation of P release kinetics. However, to our knowledge, it has never been evaluated against DGT or the porewater method. Our data suggest that EUF deserves more

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attention in future studies on plant-available P, and potentially also on other nutrients.

Soil P concentrations in relation to soil properties. All physico-chemical soil P transformations such as precipitation-dissolution and adsorption-desorption are controlled by different soil properties such as pH, carbonate and Fe (and Al) oxide contents (Peaslee and Phillips 1981). As mentioned above, P extractability in our soils was affected by pH but not by carbonate contents. It should be noted that P solubility in soils reaches its maximum at pH values around 6–6.5 as at this point several P minerals are simultaneously controlling P solubility. Therefore, soil P solubility decreases with pH deviation from this point (Lindsay 1979, Barrow 2017). Furthermore, it should be noted that in carbonate-containing soils the variation of pH is small compared to the range of pH in carbonate-free soils, although P solubility and availability may still be affected by calcite contents. Therefore, P extractability is usually correlated with soil pH, but often not with carbonate content.

Although soil P extractability and solubility in our selected P tests are influenced by different soil characteristics such as pH (except for CAL and EUF), texture and the contents of amorphous Fe oxides (except for CAL, Figure 1), multiple regression models, including different soil variables (Table 4), could not improve the relation between soil P availability and shoot biomass compared to that shown in Figure 3 (data not shown). Recena et al. (2015) showed that plant available P (Olsen-P) did not correlate with P uptake by cucumbers in high P soils, however, it could be explained by total P adsorption capacity (and affinity) of soil particles ($R^2 = 0.56$), which can significantly affect Kd and PBC.

These observations show that soil P tests, P threshold values (calibration trials) and finally, fertiliser calculation are widely affected by soil properties through influencing P solubility, sorption capacity and desorption kinetics (Jordan-Meille et al. 2012, Recena et al. 2022).

In conclusion, we compared a broad range of soil P tests in a wide range of WRB soil groups and typical range soil physicochemical characteristics acting as main controls of P solubility that remarkably differ in terms of their P availability and are representative of less weathered European soils. High and significant correlations were found among most of the investigated soil P tests, with the remarkable exception of the CAL-P. Additionally, extractable P pools by different extractants and methods showed significant correlations with soil pH (except for CAL- and EUF-P), AAO-Fe and sand content (except for CAL-P).

Our results show, that for soils of the Central European climate zone, DGT-P is among the top performing tests in determining plant-available P and correlation with plant P uptake, but does not perform better than the best-performing conventional equilibrium-based extraction methods (e.g. Olsen-P), including several quantity and intensity approaches. The relatively similar performance of DGT, intensity tests and some quantity tests suggest that our studied soils are in the transition between Q and I-controlled soils, so that the availability of P to plants is controlled by both diffusional resupply and the quantity of available P. Our observations in temperate soils with lower P buffering capacity contrast with earlier results found for highly weathered soils (larger PBC), where P supply control was dominated by diffusional resupply and strongly buffered by Al- and Fe-oxyhydroxides. Additionally, the advantage of novel infinite sink-based techniques like DGT over conventional chemical equilibrium-based approaches becomes less apparent when water availability is not a limiting factor of P diffusion.

Acknowledgements. The authors thank Erik Smolders for providing the dataset of Nawara et al. (2017) and for valuable input during several discussions. They also thank Franz Zehetner for providing the dataset of Wuenscher et al. (2015) and Veronika Slavik and Tamara Kolodziej for their great support in laboratory work.

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Received: July 16, 2025
Accepted: September 27, 2025