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Effects of variable rate fertiliser application on selected macronutrients leaching from the ploughed layer

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Abstract: In this study, the effects of standard fertilisation versus variable fertilisation with mineral and organomineral fertilisers on N, P, K, Ca and Mg leaching from the ploughed layer and yields of winter wheat and spring wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.) were studied. The losses of calcium were the highest, and phosphorus from phosphates was the lowest of all studied nutrients when simulated rainfall and lysimeters were used after the crops were harvested. The use of variable rate fertilisation reduced nitrates leaching in all the studied plots. Nevertheless, leaching of calcium, which is present in higher concentrations in soils (and also magnesium leaching), seems to be more dependent on the used fertilisers (or their combinations) and doses. As found in different studies, we proved that variable rate fertilisation may not increase grain yields.

Keywords: ammonium nitrogen; chemical soil properties; Chernozem; precision farming; texture

Variable rate fertilisation is a precision agriculture technology which allows to apply fertilisers according to plants' needs and soil status, as well as optimal placement of fertilisers in the root zone of plants (Schumann 2010). Variable rate fertilisation (or other compounds applications) does not necessary lead to higher yields of crops when compared with standard uniform rate fertilisation (Schumann 2010; Kazlauskas et al. 2022; Vaz et al. 2023; Wang et al. 2023; etc.). Nevertheless, it represents a way to reduce nutrient rates and increase the ratio between crop yields and applied nutrients. Another advantage of variable rate fertilisation is a possibility of lower nitrogen losses from soils (e.g., Burton et al. 2008; Wang et al. 2023). Jiang et al. (2018) studied the effect of root-zone fertilisation compared with split-surface broadcast fertilisation (urea). Higher nitrogen uptake and nitrogen use efficiency, as well as lower potential nitrogen losses, were related to root-zone fertilisation.

Our aim in this study was to compare the effect of zone variable fertilisation and standard surface fertilisation on leaching of different nutrients (N, P, K, Ca and Mg). Ammonium nitrogen leaching is generally low (e.g., Mancino & Troll 2019). Nitrate nitrogen is very mobile in soils, and its leaching is high,

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as shown by many publications (e.g., Fučík et al. 2008; Žlábek et al. 2008; Haberle et al. 2009; Akinbile 2012; Fraters et al. 2015; Shukla & Saxena 2020; Vogeler et al. 2021; Záruba et al. 2023; Hou et al. 2024; Zheng et al. 2024; Olšovská et al. 2025). The content of exchangeable potassium in soils, fertilisers, including the time of application and doses, soil texture (and clay content), cation exchange capacity, plants or the quantity of applied water, etc. were found to influence potassium leaching from different soils (Kayser & Isselstein 2005; Naik et al. 2021; Paltineanu et al. 2021, etc.). For example, Rodrigues et al. (2025) found higher potassium leaching from sand compared with silt or clay soil. Calcium and magnesium leaching were found to correlate with their concentrations in soil extracts; their leaching may also be influenced by plants and the quantity of applied water, texture (and cation exchange capacity), etc. (e.g., Yläranta et al. 1996). Paltineanu et al. (2021), for example, found no nutrients leaching in the case of some soil types. The use of fertilisers was found to influence calcium and magnesium leaching. The application of nitrogen fertilisers and consequent change (decrease) in soil pH and also nitrates leaching may promote calcium and magnesium leaching (e.g., Simeonova et al. 2017); the use of nitrification inhibitors or organic matter with higher C/N ratio (nitrogen immobilisation by soil microorganisms, higher retention of water in soils, etc.) may reduce nitrates, calcium and magnesium leaching losses. Phosphorus availability in soils can be influenced by changes in soil pH (and other factors), and it is supposed to be the highest when soil pH is near 6.5 (Balla Kovács et al. 2021, etc.). Positive effects of liming of acid soils (or organic matter addition) on phosphorus availability (and its mineralisation), aluminium toxicity and root growth were reported, for example (e.g., Jokubauskaitė et al. 2015). Phosphorus availability is also lower in alkaline and calcareous soils (e.g., Mete et al. 2015; Yu et al. 2020). The application of fertilisers may influence total and available phosphorus concentrations as well as soil pH (and base cations, etc.) (Medinski et al. 2018, etc.). Urea or ammonium sulphate (or NPK), for example, were described to acidify soils (as well as ammonium nitrate; for example, its effect may be intensified with the use of superphosphate and potassium salt) and organic fertilisers may increase or decrease soil pH (and may influence organic carbon content) (e.g., Čop 2014; Wang et al. 2019). Wang et al. (2019) also state that the application of pig manure led to higher soil pH, and slightly increased soil pH was found when organic (pig manure) plus mineral (NPK) fertilisers were applied. Phosphorus leaching may depend on soil properties (e.g., chemical soil properties may be less important in soils with preferential flow in macropores compared with those without preferential flow), fertilisers, land use or plants (and inputs of organic acids from plant roots) versus soils without plants, etc. (Esteller et al. 2009, etc.). The occurrence of plants may influence concentrations of water-soluble phosphorus in some soils (Balla Kovács et al. 2021, etc.).

We hypothesised reduced losses of nitrogen with the use of variable rate fertilisation (see the publications by Wang et al. 2023 or Guerrero et al. 2021), and ammonium nitrogen was hypothesised to form a low part of mineral nitrogen leaching losses (e.g., Yoon et al. 2016; Simeonova et al. 2017; Esteller et al. 2009). Of all studied nutrients, we also hypothesised the highest leaching of calcium (and the lowest leaching of phosphorus) because of its higher concentrations in soils as found by Tripolskaja et al. (2016), etc.

MATERIAL AND METHODS

The plots were established near Bořanovice, Veliká Ves, Předboj, Kojetice and Bášť (north of Prague) in the Czech Republic – a mean annual air temperature of 8–9 °C, a mean annual precipitation of 500–600 mm and a sum of air temperatures above 10 °C between 2 600 and 2 800 (warm, mildly dry region of the Czech Republic). A soil survey was realised based on yield maps (Bořanovice – spring 2021, Veliká Ves – spring 2022, Předboj – autumn 2022, Kojetice – spring 2023, Bášť – autumn 2023). The soil survey was not realised during the same year; the aim was to find the plots with winter wheat or spring barley (spring wheat) within different crop rotations. Soil samples were taken in a grid. The placement of sampling points (9–23) within the fields was realised according to yield potential maps. The values of soil properties were used to prepare maps for fertilisation. The values of soil organic carbon and total nitrogen, available potassium, calcium, magnesium, phosphorus, ammonium and nitrate nitrogen, cation exchange capacity and base saturation or soil pH are in Tables 1–3. Soil organic carbon was determined according to ISO 14235 (1998), total nitrogen according to ISO 11261 (1995), pH_{H_2O} or pH_{KCl} according to ČSN ISO 10390 (2011), cation exchange capacity and base saturation according to ISO 13536 (1995). Ca, Mg, K and P were determined in the extract Mehlich III (Mehlich1984), ammonium

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Table 1. Organic carbon, total nitrogen and pH of soils from the studied plots (mean ± standard deviation, minimum – maximum)

Locality	pH_{H_2O}		pH_{KCl}		C_{ox} (%)		N_t (%)	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Bořanovice	8.01 ± 0.15 (7.66–8.15)	8.03 ± 0.13 (7.82–8.19)	7.21 ± 0.14 (6.87–7.34)	7.23 ± 0.14 (6.99–7.40)	2.07 ± 0.60 (1.31–3.46)	1.70 ± 0.45 (0.96–2.28)	0.21 ± 0.03 (0.16–0.25)	0.19 ± 0.04 (0.13–0.24)
Veliká Ves	7.77 ± 0.08 (7.66–7.86)	7.85 ± 0.04 (7.78–7.90)	7.00 ± 0.07 (6.93–7.12)	7.05 ± 0.05 (6.99–7.14)	2.54 ± 0.30 (2.20–3.05)	2.35 ± 0.39 (1.80–2.95)	0.29 ± 0.04 (0.25–0.36)	0.28 ± 0.05 (0.21–0.35)
Bášť	7.46 ± 0.80 (6.55–8.07)	n.d.	6.72 ± 0.71 (5.92–7.26)	n.d.	1.83 ± 0.15 (1.68–1.98)	1.69 ± 0.16 (1.54–1.85)	0.24 ± 0.01 (0.23–0.25)	0.21 ± 0.02 (0.19–0.23)
Předboj	6.41 ± 0.84 (5.63–7.65)	n.d.	5.50 ± 1.00 (4.49–6.87)	n.d.	2.13 ± 0.43 (1.60–3.01)	2.09 ± 0.38 (1.74–2.75)	0.22 ± 0.03 (0.19–0.29)	0.23 ± 0.05 (0.19–0.32)
Kojetice	7.08 ± 0.73 (5.79–7.82)	n.d.	6.28 ± 0.90 (7.71–7.17)	n.d.	1.57 ± 0.17 (1.32–1.81)	1.43 ± 0.13 (1.26–1.69)	0.18 ± 0.02 (0.16–0.22)	0.17 ± 0.02 (0.13–0.20)

n.d. – not determined

Table 2. Cation exchange capacity (CEC), base saturation and concentrations of available potassium and calcium in the soils from studied plots (mean ± standard deviation, minimum – maximum)

Locality	CEC (mmol+/100 g)		Base saturation (%)		Available K (mg/kg)		Available Ca (mg/kg)	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Bořanovice	26.10 ± 3.69 (20.74–31.52)	n.d	97.2 ± 4.6 (85.0–100.0)	n.d	181.9 ± 44.9 (110.0–266.0)	159.6 ± 40.9 (94.0–207.0)	9 209.4 ± 2 494.7 (5 324.0–12 808.0)	10 049.4 ± 3 320.7 (5 411.0–15 467.0)
Veliká Ves	33.91 ± 2.18 (31.09–36.85)	33.09 ± 4.80 (24.96–39.04)	99.7 ± 0.8 (98.0–100)	99.8 ± 0.4 (99.0–100)	352.3 ± 159 (198.0–616.0)	278.7 ± 107.1 (168.0–435.0)	11 565.8 ± 1 476.4 (8 874.0–12 866.0)	11 454.3 ± 2 203.9 (8 539.0–13 850.0)
Bášť	25.82 ± 0.91 (21.19–26.86)	n.d.	n.d.	n.d.	272.7 ± 43.5 (226.0–312.0)	252.3 ± 85.1 (185.0–348.0)	6 582.3 ± 3 775.6 (3 441.0–10 771.0)	6 900.3 ± 3 679.3 (3 594.0–10 864.0)
Předboj	20.47 ± 7.32 (8.76–37.01)	23.25 ± 5.82 (18.03–34.46)	76.5 ± 19.0 (49.0–100)	80.0 ± 14.6 (56.0–98.0)	254.9 ± 54.3 (191.0–378.0)	219.4 ± 42.5 (164.0–298.0)	3 744.2 ± 2 333.2 (2 022.0–9 142.0)	3 668.5 ± 1 698.5 (2 137.0–7 325.0)
Kojetice	n.d.	n.d.	n.d.	n.d.	135.9 ± 28.7 (94.0–184.0)	127.4 ± 27.2 (87.0–170.0)	3 666.0 ± 1 454.5 (1 745.0–5,941.0)	3 761.4 ± 1 799.6 (1 682.0–6 819.0)

n.d. – not determined

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Table 3. Concentrations of available phosphorus, magnesium, ammonium nitrogen and nitrate nitrogen in the soils from studied plots (in mg/kg) (mean ± standard deviation, minimum – maximum)

Locality	Available Mg		Available P (mg/kg)		NH_4^+-N		NO_3^--N	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Bořanovice	217.9 ± 48.6 (177.0–330.0)	220.1 ± 37.3 (167.0–290.0)	20.7 ± 14.7 (5.0–53.0)	19.3 ± 15.4 (3.0–43.0)	n.d.	n.d.	n.d.	n.d.
Veliká Ves	407.0 ± 236.5 (198.0–857.0)	426.7 ± 221.9 (188.0–793.0)	26.7 ± 23.4 (9.0–65.0)	18.5 ± 18.0 (3.0–45.0)	n.d.	n.d.	n.d.	n.d.
Bášť	170.7 ± 71.2 (110.0–249.0)	172.7 ± 67.0 (106.0–240.0)	32.7 ± 22.1 (17.0–58.0)	29.0 ± 27.9 (10.0–61.0)	3.3 ± 0.8 (2.8–4.2)	5.0 ± 3.0 (2.9–8.4)	10.1 ± 2.3 (7.6–12.2)	8.6 ± 2.1 (6.9–10.9)
Předboj	201.1 ± 68.8 (143.0–350.0)	200.5 ± 49.6 (137.0–304.0)	217.7 ± 69.1 (116.0–344.0)	208.8 ± 56.3 (130.0–339.0)	n.d.	n.d.	n.d.	n.d.
Kojetice	312.8 ± 91.6 (178.0–428.0)	265.1 ± 82.2 (145.0–404.0)	81.1 ± 37.3 (24.9–139.4)	80.9 ± 34.7 (24.5–122.7)	3.7 ± 1.9 (2.5–8.6)	3.3 ± 1.0 (2.3–5.4)	12.6 ± 6.1 (7.0–26.4)	11.9 ± 4.2 (6.7–19.6)

n.d. – not determined

nitrogen and nitrate nitrogen according to ČSN ISO 7150-2 (1994) and ČSN EN ISO 13395 (1997). Five different experiments were realised on 5 plots with different soil properties (where 3 crops were cultivated). Concerning the plots near Bořanovice and Veliká Ves, the same dose of nitrogen plus different P and K doses (standard versus variable) were applied. On the plot near Předboj, compost (30 t per ha) was applied on the part of this plot with low yield potential; different doses of nitrogen (without added P and K) were tested in the case of the used standard versus variable fertilisation. Different doses of nitrogen (standard versus variable) were tested on the plot near Kojetice. We hypothesised low availability of phosphorus in case of some parts of the plot; thus, the used variable fertilisation was also with phosphorus. High mineral nitrogen concentrations were found on the plot near Bášť. Thus, nitrogen and phosphorus addition in the variant with variable fertilisation was compared with the variant without fertilisation (control). Two fertilisers (NPK – 15 : 15 : 15 or ammonium nitrate dolomite = LAD 27 – 27% N, 4% MgO) or no fertilisation were used in the case of standard fertilisation. Three fertiliser combinations were in the variants with variable rate fertilisation, including Lovostart GSH NP 6-28+7S (6% N, 28% P_2O_5, 7% S, 2% MgO, 11% CaO, B, Mn, Mo, Zn, humic acids), NPK + Lovostart GSH NP 6-28+7S or LAD 27 + Lovostart GSH NP 6-28+7S. The fertilisers were applied during sowing (winter wheat – the beginning of October, spring barley and spring wheat – the end of March and at the beginning of April). Physical and chemical soil properties, including the content of nutrients in soil, soil depth, etc. were taken into account to apply different doses of nutrients (and the number of nutrients – see Table 4). Winter wheat (Bořanovice, 2.06 ha), spring barley (Veliká Ves, 7.13 ha), winter wheat (Předboj, 13.98 ha), spring wheat (Kojetice, 9.72 ha) and winter wheat (Bášť, 5.3 ha) were cultivated on the studied plots. Selected nutrients leaching was studied using rainfall simulation (100 mm, 1 mm/min) after the crops were harvested (July 27, 2022 = Bořanovice, July 27, 2023 = Předboj, August 22, 2023 = Kojetice, July 31, 2024 = Bášť). Dry soil was the reason why 200 mm of simulated rain (not 100 mm) was applied on the plot near Veliká Ves (August 3, 2022). On the studied plots, 4 lysimeters were used for standard fertilisation and 4 lysimeters for variable fertilisation (variable fertilisation = 2 variants and 2 lysimeters per variant). Different soil types (Chernozems and

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Table 4. The amount of applied nutrients (N, P, K) on the studied plots

Locality (soils)[a]	USDA textural classes[b]	Fertilisation	Fertiliser	Dose	Applied N	Applied P_2O_5	Applied K_2O
				(kg/ha)			
Bořanovice (Chernozems)	silty loam, silty clay loam, silty clay and clay loam	standard	NPK (15:15:15)	140	21	21	21
		variable	Lovostart GSH NP 6–28 + 7S	350	21	98	–
		control	–	–	–	–	–
Veliká Ves (Chernozems)	clay loam and clay	standard	NPK (15:15:15)	100	15	15	15
		variable	NPK (15:15:15) plus Lovostart GSH NP 6–28 + 7S	68 + 80	15	33	10
Předboj[c] (Chernozems and Cambisols)	not determined	standard	LAD 27	three applications (193/193/96)	130	–	–
		variable	LAD 27	three applications (167/167/74 or 148/148/56)	first zone – 110 second zone – 95	–	–
Kojetice (Chernozems and Cambisols)	loam and silty loam	standard	LAD 27	200	54	–	–
		variable	LAD 27 plus Lovostart GSH NP 6–28 + 7S	140 + 60 (LAD) plus 40 (Lovostart) or 170 + 70 (LAD) plus 40 (Lovostart)	first zone – 56 second zone – 67	first zone – 11 second zone – 11	–
Bášť (Chernozems and Regosols)	clay loam	standard	–	–	–	–	–
		variable	Lovostart GSH NP 6–28 + 7S	240 or 265	first zone – 14 second zone – 16	first zone – 67 second zone – 74	–

[a]IUSS Working Group WRB (2015); [b]Soil Science Division Staff (2017); [c]on a part of this plot (with low yield potential), compost (30 t/ha) was also applied; the soils are developed on loess, marl, silicites, etc.

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Cambisols) were not taken into account on the plot near Kojetice. The placement of lysimeters within the plots near Předboj and Bášť was realised with respect to the soil types (Chernozems or Cambisols, Chernozems or Regosols) (Table 4) – the lysimeters for different variants were related to different soil types. The lysimeters were composed of drain water bottles – 2-liter PVC flasks (Ø 12.5 cm) with narrow necks. The extraction of water was realised using barrel funnels (PVC, Ø = 30 cm, 0.07 m^2). After the narrow necks were cut off, the funnels were inserted and sealed. The funnels were lined with geotextile Netex (and vertical thin wall tubes were used for water suction), filled with granite gravel 4/8 and covered with geotextile. The collecting area of lysimeters was 25 cm below the surface. Ammonium ions and nitrates in lysimetric water were determined according to ČSN ISO 7150-2 (1994) and ČSN EN ISO 13395 (1997); potassium or calcium (and magnesium), phosphates were determined according to ČSN ISO 9964-2 (1996) or ČSN ISO 7980 (1994), ČSN EN 1189 (1998). The nutrients were determined in one repetition per lysimeter. The differences in the values were submitted for testing using a *t*-test. When the assumptions about a parametric test (homogeneity of variance, normality) were not met (even after a log transformation of values), a Mann-Whitney U test was used. All statistical analyses were performed with STATISTICA (Ver. 10, 2011).

RESULTS AND DISCUSSION

Bořanovice. Concerning the plot near Bořanovice and the variants with standard fertilisation (NPK), variable fertilisation (Lovostart GSH NP 6-28+7S) and without fertilisation (= control), the nutrients in lysimetric water recalculated per 1 ha were Ca > NO_3^--N > Mg > K > PO_4^{3-}-P. The average values of Ca, NO_3^--N and Mg losses were the lowest in the variant with variable rate fertilisation (Table 5). These losses were by 41% (Ca), 23% (NO_3^--N) and 28% (Mg) lower in the variant with Lovostart compared with NPK. Potassium leaching was from 0.4 to 0.9 kg/ha (and was similar for both Lovostart and NPK). PO_4^{3-}-P in lysimetric water was from 0.005 to 0.007 kg/ha. In all variants, ammonium nitrogen in lysimetric water formed only 0.2–1.2% of mineral nitrogen (NO_3^--N + NH_4^+-N). Additionally, 103.7% of the applied nitrogen (Table 4) was leached in the variant with standard fertilization (as nitrate nitrogen) compared with 80% in the variant with variable rate fertilisation. 3% of applied potassium was leached in the variant with standard fertilisation. Phosphorus losses from the used fertilisers were low (0.03% and 0.15%).

Veliká Ves. The used variable application of NPK + Lovostart led to reduced NO_3^--N (by 56%) and higher Ca and Mg losses (by 101% and 127%) compared with the standard NPK fertilisation (Table 5). A higher amount of potassium was found in the variant with variable rate fertilisation (1.5 versus 1.3 kg/ha). PO_4^{3-}-P losses were in the range from 0.02 to 0.04 kg/ha. Ammonium nitrogen losses were < 0.3% of mineral nitrogen. Further, 132% of applied nitrogen was leached (as nitrate nitrogen) in the variant with NPK (and 10% of applied potassium) compared with 59% in the case of the variant with NPK + Lovostart (and 19% of applied potassium). Phosphorus losses were low (1.2% = NPK and 0.3% = NPK + Lovostart).

Předboj. The losses of nutrients were in the order Ca > K > NO_3^--N > Mg (standard – LAD 27), Ca > K > Mg > NO_3^--N (variable – LAD 27, 167/167/74) and Ca > Mg > K > NO_3^--N (variable – LAD 27, 130/130/37) on the plot near Předboj (see Table 5). The values for K losses were 2.6 kg/ha (standard), 1.7 kg/ha (variable – LAD 27, 130/130/37) and 2.0 kg/ha (variable – LAD 27, 167/167/74). The used variable rate application of LAD 27 led to lower NO_3^--N (by 50%) and K (by 23–32%) losses compared with the standard rate of LAD 27. PO_4^{3-}-P losses were in the range from 0.1 to 0.2 kg/ha. Ammonium nitrogen was 5% to 16% of mineral nitrogen. Also, 1.0–1.8% of applied nitrogen from LAD 27 was in lysimetric water.

Kojetice. The losses of individual nutrients were in the order Ca > Mg > K > NO_3^--N (standard – 200 kg/ha LAD 27, variable – 170 + 70 kg/ha LAD 27, 40 kg/ha Lovostart) and Ca > K > Mg > NO_3^--N (variable – 140 + 60 kg/ha LAD 27, 40 kg/ha Lovostart). The result of variable fertilisation was lower Ca, Mg and NO_3^--N (by 37%, 27% and 8%) in lysimetric water, and it was only in the zone with LAD 27 (140 + 60 kg/ha) and Lovostart (40 kg/ha) (Table 5). The average value of K losses was the lowest in the standard variant (1.8 kg/ha versus 2.7–2.9 kg/ha). PO_4^{3-}-P losses were from 0.06 to 0.2 kg/ha. Ammonium nitrogen losses were 3% to 13% of mineral nitrogen. Also, 2–3% of applied nitrogen from LAD 27 or LAD 27 + Lovostart were leached in the form of nitrate nitrogen; 4.4% and 8.8% of applied phosphorus (LAD 27 + Lovostart) were leached.

Bášť. The average losses were Ca > NO_3^--N > Mg > K > PO_4^{3-}-P. The use of variable rate fertilisation

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Table 5. Calcium, nitrate nitrogen, magnesium, potassium and phosphorus from phosphates leaching on the studied plots

Locality	Fertilisation	Fertiliser	Calcium	Nitrate nitrogen	Magnesium	Potassium	Phosphorus from phosphates
			(kg/ha)				
Bořanovice	standard	NPK	64.2	21.7	4.6	0.5	0.007
	variable	Lovostart	38.1	16.7	3.3	0.4	0.006
	control	–	55.2	10.7	4.3	0.9	0.005
Veliká Ves	standard	NPK	16.4	19.8	1	1.3	0.04
	variable	NPK plus Lovostart	33	8.8	2.3	1.5	0.02
Předboj	standard	LAD 27	12.9	2.3	1.9	2.6	0.13
	variable	LAD 27 (167/167/74)	11.8	1.1	1.7	2.0	0.12
		LAD 27 (130/130/37)	13	1.1	1.8	1.7	0.16
Kojetice	standard	LAD 27	15.1	1.1	2.3	1.8	0.06
	variable	LAD 27 (140 + 60 kg/ha) plus Lovostart (40 kg/ha)	9.5	1.1	1.7	2.9	0.11
		LAD 27 (170 + 70 kg/ha) plus Lovostart (40 kg/ha)	21.1	2	3.8	2.7	0.21
Bášť	standard	–	43.3	8.2	4.5	1.3	0.007
	variable	Lovostart (265 kg/ha)	47.4	7.5	6.0	1.5	0.04
		Lovostart (240 kg/ha)	36.5	3.6	2.3	2.0	0.03

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led to reduced losses of Ca, Mg and NO_3^--N (by 15%, 50% and 56%) in case of Lovostart (240 kg/ha) (Table 5). The losses of Ca and Mg were the highest in the case of Lovostart (265 kg/ha). The highest potassium leaching (2 kg/ha) was in the variant with Lovostart (240 kg/ha) compared with 1.3 kg/ha (control) and 1.5 kg/ha (Lovostar, 265 kg/ha). PO_4^{3-}-P losses were 0.007–0.04 kg/ha; ammonium nitrogen losses formed 0.2–1.7% of mineral nitrogen. On the plot near Bášť, 23% and 54% of applied nitrogen from Lovostart (265 and 240 kg/ha) were leached (and 0.2% of phosphorus).

All studied plots. Concerning the statistical testing, *P*-values from a Shapiro-Wilk W test are in Table 6 (*P*-values for homogeneity of variance are 0.050–0.966). The effect of variable rate fertilisation on Ca, Mg, NO_3^--N and K in lysimetric water was not significant ($P > 0.05$) on the studied plots (Table 7). It was significant ($P < 0.05$) only in the case of PO_4^{3-}-P on the plots near Kojetice and Bášť. Simeonova et al. (2017) state that nitrates can influence calcium and magnesium leaching. Thus, we tested correlations between NO_3^--N - and Ca (or Mg). We found significant correlations between NO_3^--N and Ca ($r = 0.85$) or NO_3^--N and Mg ($r = 0.62$). The values of yields were slightly higher in the case of the used variable fertilisation; the exception was only the locality near Předboj with 6.93 t/ha (variable) versus 7.82 t/ha (standard). The assumptions about a parametric test were met in the case of crop yields testing. The effect of variable rate fertilization on crop yields was not significant ($P > 0.05$) (Figure 1).

In this study, the losses of calcium were the highest of all studied nutrients (see Adomaitis et al. 2013, Tripolskaja et al. 2016, etc.). For example, Adomaitis et al. (2013) found that different rates and combinations of NPK fertilisers led to nutrients leaching in the order $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ (sandy loam, neutral or slightly alkaline). According to the authors, Ca^{2+} leaching was influenced by the used fertilisers and their rates (e.g., effects of NH_4^+ and K^+ on Ca^{2+} sorption or uptake by plants, Ca added with the used fertilisers, changes of soil pH, effects of nitrates leaching). The losses of Ca in this study (all studied plots) ranged from 9 to 64 kg/ha. The values from 84 to > 400 kg Ca/ha/year were reported in some other studies related to differently fertilised land (e.g., Adomaitis et al. 2013; Tripolskaja et al. 2016). The second largest losses are related to nitrate nitrogen (Bořanovice, Veliká Ves, Bášť). Sestak et al. (2014) studied the effect of variable nitrogen fertilisation (0–300 kg/ha) on winter wheat grain yields, nitrogen use efficiency and NO_3^--N in lysimetric waters. The authors state the effect of individual

Table 6. *P*-values from a Shapiro-Wilk W test

Experimental plot	Leached nutrient				
	nitrate nitrogen	calcium	magnesium	potassium	phosphorus
Bořanovice	0.181	0.050	0.001	0.797	0.937
Veliká Ves	n.t.	n.t.	n.t.	n.t.	n.t.
Bášť	0.508	0.430	0.171	0.236	0.594
Předboj	0.151	0.043	0.039	0.598	0.554
Kojetice	0.235	0.073	0.713	0.127	0.058

n.t. – not tested

Table 7. *P*-values from statistical testing – standard fertilisation versus variable rate fertilisation

Experimental plot	Leached nutrient				
	nitrate nitrogen	calcium	magnesium	potassium	phosphorus
Bořanovice	0.384	0.286	0.667	0.096	0.739
Veliká Ves	n.t.	n.t.	n.t.	n.t.	n.t.
Bášť	0.369	0.903	0.837	0.363	0.003
Předboj	0.126	0.843	0.771	0.375	0.883
Kojetice	0.735	0.486	0.957	0.217	0.029

n.t. – not tested

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years on N uptake by plants and its losses; the relationship between nitrogen use efficiency (decreasing with increasing N rates) and total losses of NO_3^--N was strong only in some of the studied years. Compared with the vales for NO_3^--N losses obtained in this study (1–22 kg/ha), the authors reported total losses of NO_3^--N (the values are presented only in one of the figures) from < 10 kg/ha to > 30 kg/ha (see Figure 5 in the publication by Sestak et al. 2014). Kokulan et al. (2022) studied NO_3^--N and total phosphorus losses (lysimeters) on the agriculturally used plots with application of chemical fertiliser or liquid swine manure (the period 2005–2016) – cool subhumid climate (precipitation = 457 mm/year), chernozemic soils (coarse-textured), the cultivation of red spring wheat and barley. Water percolation and nutrient losses differed within and between the studied years. The authors state the highest NO_3^--N and total phosphorus losses in the years following a dry year. The authors found the highest losses of NO_3^--N on the plots with chemical fertilization (22.47 kg/ha) and the lowest losses in the case of the control without fertilisation (15.53 kg/ha). In this study, the losses of ammonium nitrogen were only < 0.3–16% of mineral nitrogen losses. Yoon et al. (2016) state that ammonium nitrogen formed only 2–15% of mineral nitrogen in seepage water collected using passive capillary samplers from grasslands and arable land. Magnesium losses were 1–6 kg/ha and potassium losses were 0.4–2.9 kg/ha in this study. From 10 to 86 kg/ha/year of magnesium and < 1.5 to 19 kg/ha/year of potassium are reported in some other studies on differently fertilised arable land (e.g., Adomaitis et al. 2013; Tripolskaja et al. 2016). Potassium leaching may, for example, depend on plant requirements, potassium fertilisers or previous history of fertiliser application. For example, Adomaitis et al. (2013) state the highest K^+ losses when high rates of potassium and phosphorus were used without nitrogen. Tripolskaja et al. (2016) found only low effects of manure types (with or without NPK), green manure or timing of undersowing plants and barley straw incorporation on potassium leaching. As stated in different publications, Chernozems (dominant soils in this study) are high fertility soils with large reserves of phosphorus (and potential to maintain P availability). High P availability in these soils can be related to pH 6–7 (reduced formation of Fe and Al phosphates, high dissolution of Ca phosphates, etc.), etc. (e.g., Balla Kovács et al. 2021). It is stated in different publications that these soils should also be fertilized with phosphorus to ensure high yields (e.g., Balla Kovács et al. 2021). Nevertheless, continuous fertilisation with phosphorus (e.g., manure) may lead to P saturation and higher phosphorus losses (Kokulan et al. 2022, etc.). In this study, the values of pH (in water) of soils were also ca. 8.0. Mete et al. (2015) reported that NPK, biochar or biochar + NPK added to highly alkaline soil reduced soil pH (and phosphorus availability was higher). Properties of topsoil seem to be important when phosphorus is also leached via macropore flow; phosphorus sorption in subsoil can be important when its leaching is not via macropores (Esteller et al. 2009). Esteller et al. (2009) reported a concentration of PO_4^{3-} in soil water < 2 mg/L, and Yoon et al. (2016) found 0.4–1.9 mg/L of mineral phosphorus in water collected using passive capillary samplers. Godlinski et al. (2004) state maximum total phosphorus concentrations from < 0.01 to 1.8 mg/L. Phosphorus losses may not correspond with the application of P fertilisers (Godlinski et al. 2004). In this study, the concentrations of PO_4^{3-}-P in water collected via lysimeters (not shown in the previous text) were in the range from 0.02 to 0.80 mg/L; PO_4^{3-}-P losses were 0.005–0.20 kg/ha. Godlinski et al. (2004) studied leaching losses (lysimeters) of total phosphorus from soil (different crop rotations, fertilisation, irrigation) with different texture (sand, sandy loam, loam, silt). The authors state that the volumes of annual leachate were influenced by soil texture (different water-holding capacity) (e.g., Godlinski et al. 2004; Da Costa et al. 2013; Vopravil et al. 2021). The highest total phosphorus losses

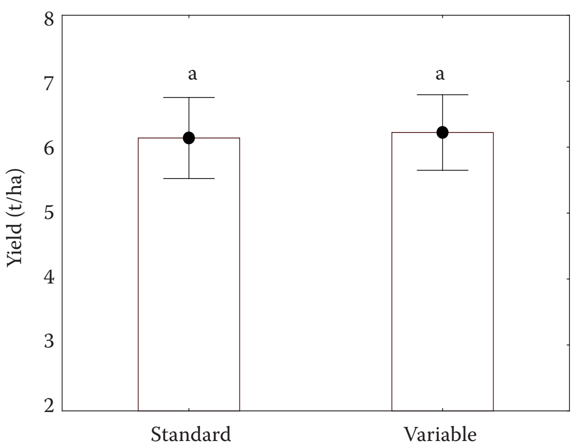

Figure 1. The effect of standard versus variable rate fertilisation on the values of yields (mean ± standard error)
Different letters mark significant ($P < 0.05$) differences between the types of fertilisation

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were from sand (0.38–2.85 kg/ha); the losses from the other soils were < 0.001 to 0.319 kg/ha.

In this study, the variable rate fertilisation did not lead to higher yields on all studied plots. The average value from these plots was similar to that from the plots with standard fertilisation. Jiang et al. (2018) found that root-zone fertilisation with reduced N application led to higher crop yields; nevertheless, yields can be higher only in some of the studied years. Both higher or lower economic return in case of variable rate fertilisation were reported in different studies (e.g., Kazlauskas et al. 2022; Wang et al. 2023). Medinski et al. (2018) found higher yields of cereals (spring barley, winter wheat) on long-term fertilised Chernozems when fertilisers also contained phosphorus. Phosphorus availability was reported to be restricted in alkaline soils (in this study, soil pH in water ranged from 5.63 to 8.19). Mete et al. (2015), for example, found a positive effect of fertilisation (NPK, biochar or biochar + NPK) on yields and nodulation of soybean cultivated in soil with pH 8.8.

CONCLUSION

In conclusion, the results of this study showed that variable rate fertilisations may not lead to higher cereal yields. Nevertheless, the obtained results indicate that the use of variable rate fertilisation may have environmental benefits, and nitrate nitrogen leaching losses from soils may be lower. Nevertheless, it was not proved statistically in this study. Leaching of calcium, magnesium and potassium was proved to be in the order of their concentrations in soil. Calcium leaching was the highest (and phosphorus from phosphates leaching the lowest) of all studied nutrients, as reported in different publications. Calcium concentrations in soils are high, and their leaching (and magnesium leaching) seems to be more dependent on the used fertilisers (or their combinations) and rates.

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