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EFFECT OF POTASSIUM BUDGET ON EVOLUTION OF SOIL POTASSIUM IN DIFFERENT CROP SEQUENCES AND SITE CONDITIONS

MIKULÁŠ MADARAS

Crop Research Institute, Prague

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The influence of six different crop sequences on the dynamics of topsoil available and fixed potassium (K_{avail} and K_{fix}) was studied within a 4-year period at 6 sites of different soil and climatic conditions. The highest K offtakes were recorded for 3-year alfalfa / clover cropping followed by winter wheat (–151 kg K/ha/year) and for the crop sequence including one year of sugar beet / potato (–124 kg K/ha/year). K_{avail} and K_{fix} were significantly decreased especially at crop sequence with alfalfa / clover cropping, compared to other crop sequences. At three sites of lower Kfix content (340–830 mg K/kg), differences in K_{avail} and K_{fix} between crop sequences were more frequent, whereas almost no significant differences between treatments were observed at sites of higher K_{fix} content (1,000–1,380 mg K/kg). Changes of both K forms and K budget correlated significantly at sites of lower K_{fix} content. At these sites, K_{avail} decreased at the rate of 0.045 mg K per 1 kg/ha of K offtake; the rate of K_{fix} decrease was 0.059 mg K per 1 kg/ha of K offtake. At sites of higher K_{fix}, no significant relation between K forms and K budget was observed. The results show an importance of K_{fix} as a K source in intensive agricultural systems with low or no K inputs.

Key words: fertilisation, nutrients, budget, balance, non-exchangeable potassium

Although the use of potassium (K) fertilisers increased by 25% since 1980 in global scale (Zörb *et al.* 2014), their application decreased dramatically in northern and western Europe (Öborn *et al.* 2005). In the Czech Republic, the use of K fertilisers dropped after 1989 from the level of ca. 70 kg K_2O/ha to the level as low as ca. 10 kg K_2O/ha (Grzebisz *et al.* 2010). Recent K input to agricultural soils is at the level of 5 kg K/ha in the form of mineral fertilisers. In addition, 18 kg K/ha is applied in the form of manures (Anonymous 2013). Overall field K offtake by harvested products is estimated to 71 kg K/ha on average (Klír *et al.* 2008); the exact offtake depends on the selection of crops and their yields.

With insufficient external K input, plant demand for K is fulfilled by previously bound fertiliser K and by internal soil K sources. K content in soils ranges from 0.4 to 30 g/kg. Only 2–10% of soil K is available to plants, the main pool is present as hardly available structural K in K-bearing feldspars and layer silicates (Huang 2005; Zörb *et al.* 2014). The term "available K" (K_{avail}) is often used in agronomy for the pool consisting predominantly of water-soluble and exchangeable K. Non-exchangeable K is another significant pool available to plants, too. This pool, called also reserve K, interlayer K or fixed K (K_{fix}), is neither bonded covalently within the crystal structures of mineral particles nor is exchangeable. Its relation to exchangeable and water-soluble K is weak (Torma 1999). K_{fix} is moderately to less available to plants, depending on soil properties (Martin & Sparks 1985). A release of K_{fix} to easily available forms is forced by plant K removal, microbial activity and by K leaching (Moritsuka *et al.* 2004; Martin & Sparks 1985). The measurement of K_{fix} is often suggested to improve prediction of K availability

RNDr. Mikuláš Madaras, PhD., Crop Research Institute, Drnovská 507, 16106 Prague 6 – Ruzyně, Czech Republic. E-mail: madaras@vurv.cz

to plants (Neuberg 1980; Rees 2013; Edmeades *et al.* 2014), but in the Czech Republic these analyses were not included within the common testing of agricultural soils.

As it is known from long-term field fertilisation experiments, non-use of K fertilisers leads first to the decrease of K_{avail} and afterwards to the stabilisation of K_{avail} at a certain level ranging from 30 to 120 mg K/kg (Blake *et al.* 1999). At this stage, further K uptake is compensated by K release from K_{fix}. Our previous research concerning long-term experiments with graduated K input indicated at some sites that the more negative is K budget, the more intensive is depletion of both K_{avail} and K_{fix} (Madaras *et al.* 2014). The decrease of K_{fix} can have the same magnitude as the decrease of K_{avail}. In some cases, the whole K offtake can originate from K_{fix} pool (Øgaard & Hansen 2010).

The experimental design of graduated fertiliser rates is common in short-term and long-term field fertilisation experiments, while other factors such as crop sequence are usually uniform for all trial plots (Blake *et al.* 1999; Øgaard & Hansen 2010; Hejcman *et al.* 2013; Madaras *et al.* 2014). However, crops differ in their nutrient uptake, which consequently have an influence on the nutrient budget. Some crops have also specific mechanisms or adaptations by which they can increase the uptake from K_{fix} (Rengel & Damon 2008). To study the influence of different crop plants on short-term soil K changes in agricultural systems without K input, we established the 4-year field experiment where different crop sequences were included as treatments. The objective of the research presented in this paper is to evaluate the influence of selected typical crop plants and their sequences on evolution of soil K.

MATERIAL AND METHODS

Experimental design

Field small-plot experiment was established at 6 sites with different climatic and soil conditions (Table 1). Sites were selected from the research station network of the Crop Research Institute, Prague. At each site, the experiment consisted of 24 plots of the size 3 × 10 m. An experimental design included 6 treatments, differing by the sequence of typical crop plants (Table 2). Treatments were replicated four times at each site. The same crop varieties and the same fertilisation scheme were used at all sites, with respect to particular crop production region. At colder sites, sugar beet was replaced by potato and alfalfa was replaced by clover. Treatments A, B, C and D differed only by the crop in the 2nd year of the experiment. Treatment E represented fodder production and included crops with high K uptake (alfalfa / clover). Treatment F was soil without vegetation cover within the first 3 years, weeds were suppressed chemically or mechanically when it was necessary. Exceptions of the uniform design were (1) the use of mustard or spring rapeseed instead of winter rapeseed after damage in winter 2010/2011 and (2) cropping of winter triticale instead of winter

T a b l e 1

Basic characteristics of experimental sites and soils

Site	Soil type	A [m]	T [°C]	R [mm]	Reg	Clay [%]	C_{ox} [%]	pH (KCl)	K_{avail}	K_{fix}	P_{avail}
									[mg/kg]		
Ivanovice na Hané	Chernozem	220	9.2	548	SB	24	2.2	6.5	186	1,050	177
Hněvčeves (HK)	Luvisol	265	8.1	597	SB	14	1.2	6.4	173	800	73
Kostelec n. Orlicí	Luvisol	290	8.0	696	SB	16	1.1	6.3	145	500	62
Prague (Ruzyně)	Luvisol	345	7.9	472	SB	19	1.5	6.8	187	1,010	62
Pernolec (Tachov)	Cambisol	530	7.1	559	POT	9	1.1	6	99	1,350	71
Vysoké n. Jizerou	Cambisol	670	6.0	1,000	FOD	13	2.1	5.5	207	350	12

A – altitude, T – mean air temperature, R – annual sum of rainfall, Reg – production regions (SB – sugar beet, POT – potato, FOD-fodder crop), Clay – fraction <0.002 mm, K_{avail} and P_{avail} – available nutrients (Mehlich III extraction), K_{fix} – fixed K wheat in site Vysoké. Overview of the weather conditions during the experiment is presented in Figure 1 and Table 3.

Sampling and analyses

Plant main product and by-products were harvested each year. Harvested material was weighed at actual moisture. Representative samples of the plant material were taken for further laboratory analyses, which includes determination of moisture content (drying at 105°C until a constant weight) and total K content (total microwave digestion). K offtake by harvested material was expressed in kg/ha. Because none K was applied in fetrilisers during the experiment, K offtake is equal to the K budget.

Soil samples of the plough horizon (0–20 cm) were taken from each plot after the harvest of the last crop. Each sample consisted of 5–8 subsamples. Samples were dried at room temperature and sieved through 2 mm mesh. Two pools of soil K were analyzed. K_{avail} was extracted by the Mehlich 3 method (Mehlich 1984). K_{fix} was calculated as K extracted by 1 mol/l HCl (1:10 w/v, incubation 20 h at 50°C; adapted from Scheffer & Schachtschabel 1976) subtracted by K_{avail}. Extracts were analyzed twice by AAS GBC 908AA. Statistical evaluation of the results was performed using the STATISTICA 12 software (Statsoft).

T a b l e 2

Crop sequences and fertilisation [kg nutrient/ha]

Sequence code	2010		2011		2012			2013		
	Crop	N1+N2	Crop	N1+N2	Crop	N1+N2	P	Crop	N1+N2	P
A	ww	50+50	ww	40+60	bar	50+50	30	ww	40+60	40
B	ww	50+50	pea	0+30	bar	50+50	30	ww	40+60	40
C	ww	50+50	sb / pot*	60+40	bar	50+50	30	ww	40+60	40
D	ww	50+50	rap / mus*	40+30	bar	50+50	30	ww	40+60	40
E	alf / clo*	0	alf / clo*	0	alf / clo*	0	0	ww	40+60	40
F	fallow	0	fallow	0	fallow	0	0	ww	40+60	40

ww – winter wheat (triticale was used instead of winter wheat in all cases at Vysoké nad Jizerou), alf / clo – alfalfa / clover, sb / pot – sugar beet / potato, rap / mus – rapeseed / mustard, bar – spring barley
* – latter crop was used in Pernolec and Vysoké nad Jizerou

T a b l e 3

Overview of the weather conditions during the experiment

Site	2010				2011				2012				2013			
	I–XII		IV–IX		I–XII		IV–IX		I–XII		IV–IX		I–XII		IV–IX	
	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T
Ivanovice	826	8.4	637	15.6	438	9.5	350	16.4	482	9.6	331	16.7	551	9.2	379	15.7
Hněvčeves	792	8.4	591	15.6	552	9.4	361	16.0	772	9.1	518	15.9	615	8.9	424	15.3
Kostelec	900	8.2	696	14.9	672	9.3	508	15.7	656	9.0	415	15.7	680	8.8	465	15.0
Prague	679	8.9	531	15.4	605	9.6	437	16.2	563	9.8	437	16.3	731	8.3	559	15.3
Pernolec	693	7.1	382	13.9	554	8.7	361	15.0	459	8.3	278	14.6	554	7.7	372	13.9
Vysoké	1,231	5.8	733	12.8	984	7.3	598	13.7	1,127	6.2	529	13.7	969	6.6	534	12.7

R – annual sum of rainfall, T – mean air temperature

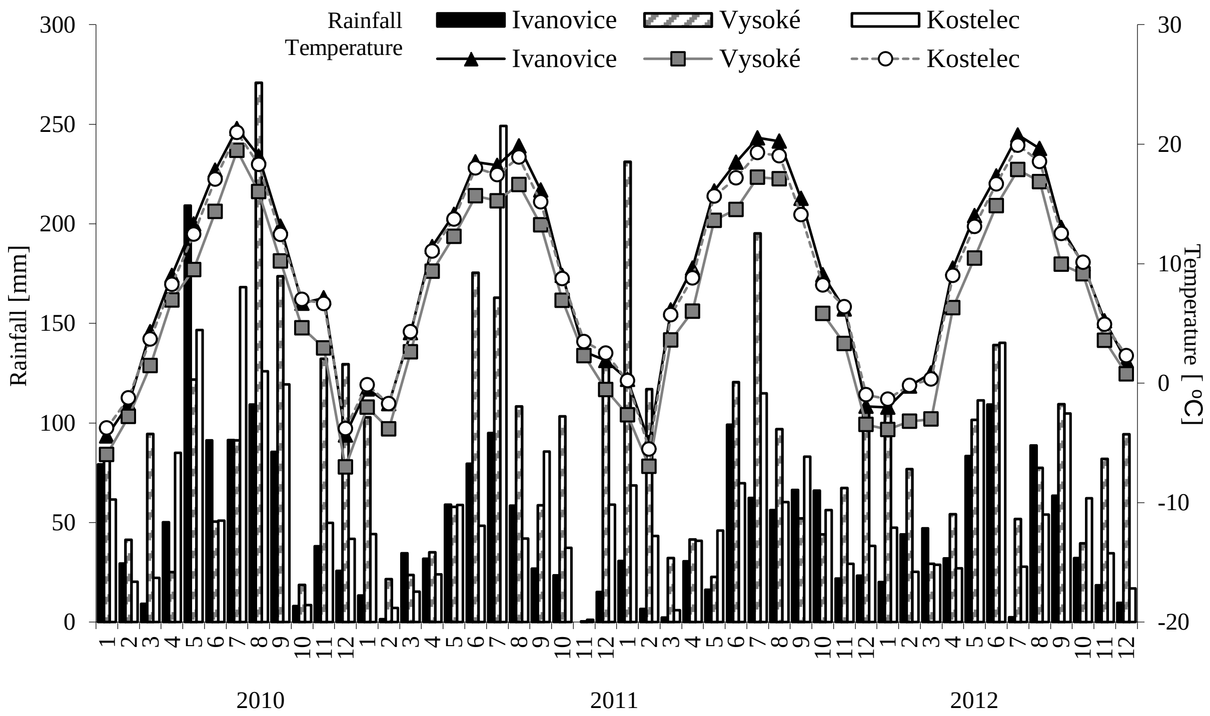

Figure 1. Overview of the weather conditions during the experiment (selected sites)

RESULTS

Yields and K uptake

Crop yields differed widely among experimental sites (Table 4). On average, they reached or exceeded average yields in the Czech Republic in particular years. The only exception was very low yield of rapeseed in 2011 due to the unfavourable late-winter and spring weather conditions at sites Hněvčeves, Prague and Ivanovice. High intensity of weed attack (e.g. *Apera spica-venti*) was one of the main reasons of low yields of winter wheat in Pernolec. Low rainfall caused decreased alfalfa yields in Ivanovice, especially in 2012.

Calculated K uptake by crops is shown in Table 5. The highest annual uptake (327 kg K/ha on average in 2011) was recorded for sugar beet / potato cropping, with maximum of 415 kg K/ha in Hněvčeves. By-products (leaves of sugar beet, stems and leaves of potato) accounted for 56% of K uptake. The second largest annual K uptake was recorded for alfalfa / clover during the 2nd and 3rd year of the experiment. On average, 244 kg K/ha was taken up annually by three cuts of hay. The lowest uptake was recorded for spring barley and for rapeseed. In the latter case, low uptake was caused both by low yield and by naturally low K concentration in the rapeseed biomass. Average annual K uptake by winter wheat was 59 kg K/ha; 41% of it accounted for grain. Triticale, as a replacement of winter wheat in Vysoké, showed more than 2-times higher K uptake compared to winter wheat because of higher straw K content (1.1% K in triticale straw, 0.6% K in winter wheat straw).

The crop variations in K uptake are reflected in average K budgets for treatments. The most negative K budget was calculated for treatment E (–184 kg K/ha/year; average of 2011, 2012 and 2013), which was followed by the treatment C (–150 kg K/ha/year). In order of increasing K budget, next crop sequences were B (–59 kg K/ha/year), A (–54 kg K/ha/year), D (–53 kg K/ha/year) and F (–26 kg K/ha/year; here only K uptake by winter wheat in 2013 was accounted).

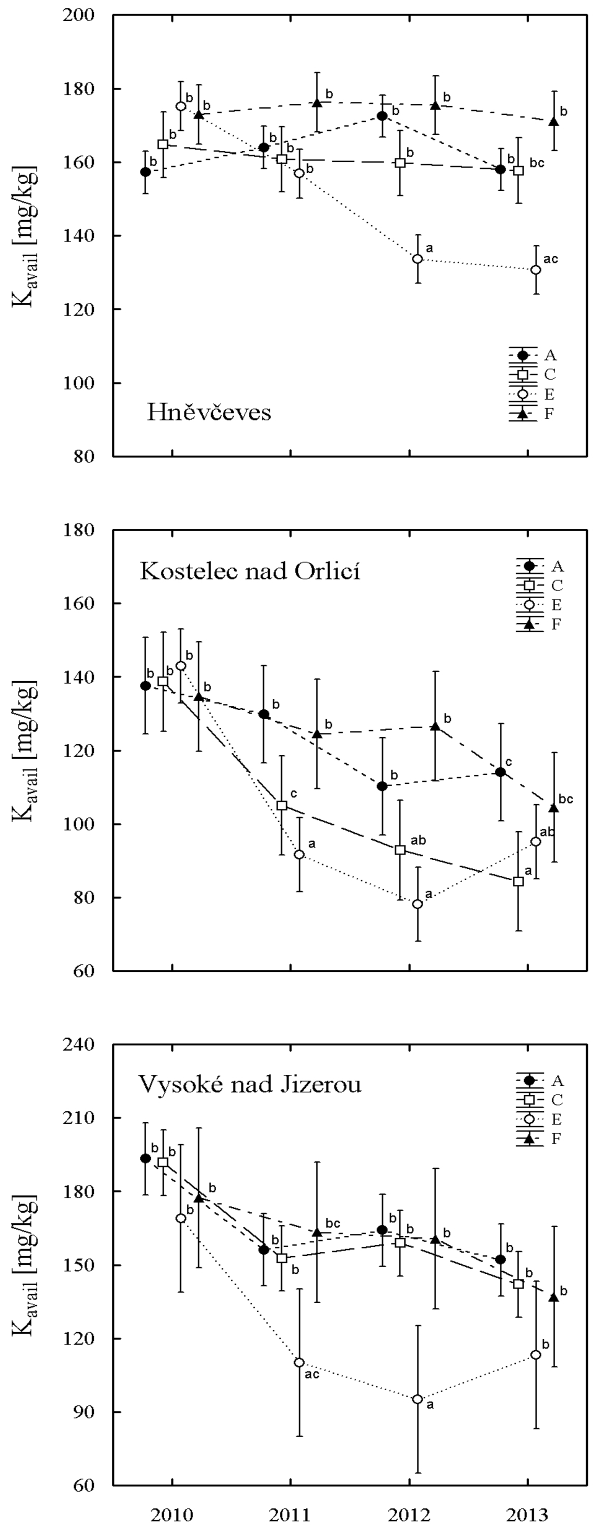

Figure 2. Available K contents at sites of fixed K < 1,000 mg K/kg (arithmetic mean and standard deviation). In particular years, significant differences ($P < 0.05$) between treatments A, C, E and F are marked by different letters.

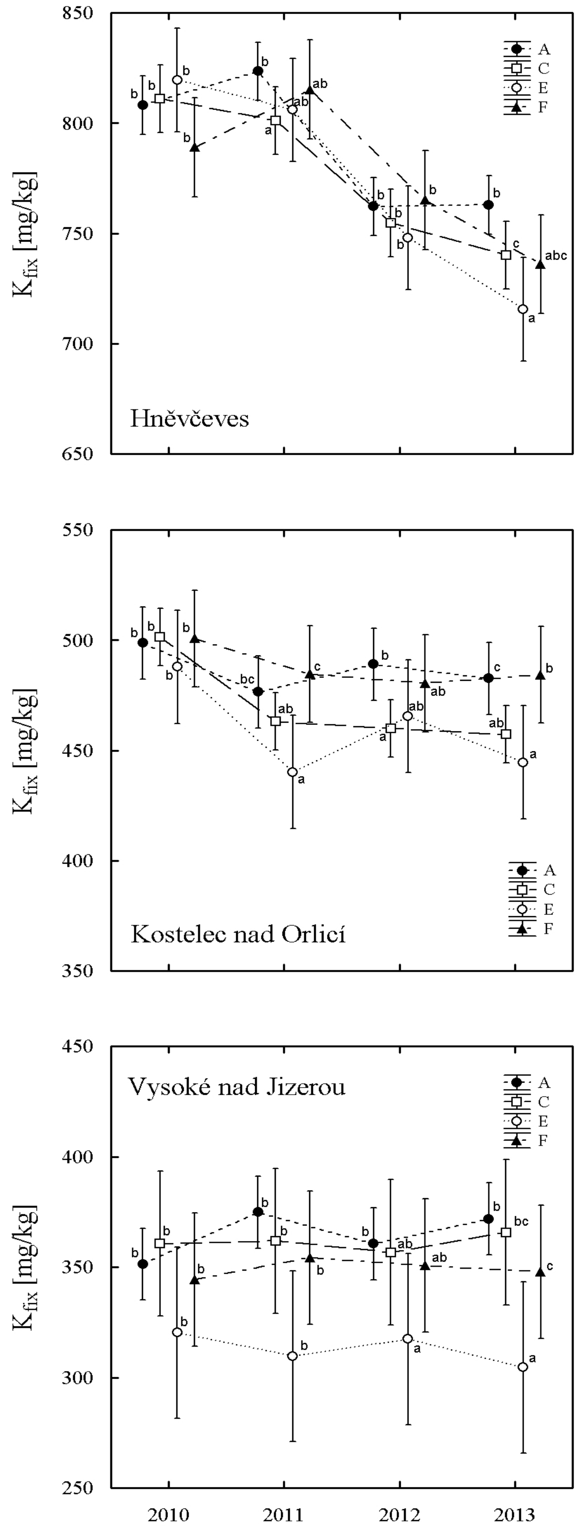

Figure 3. Fixed K contents at sites of fixed K < 1,000 mg K/kg (arithmetic means and standard deviation). In particular years, significant differences ($P < 0.05$) between treatments are marked by different letters.

Soil available potassium

Remarkable changes of K_{avail} were observed especially in Vysoké, Kostelec and Hněvčeves (Figure 2). At these 3 sites, K_{avail} of the treatment E was clearly different from other treatments. In Hněvčeves, K_{avail} at crop sequence E was significantly lower than at other crop sequences in years 2012 and 2013 ($P < 0.01$ for almost all Student tests between treatments); however there were no significant differences among other crop sequences. During the experiment, K_{avail} remained approximately at the same level, with exception of the continuous decrease by alfalfa cropping within 2010 and 2012 at treatment E.

In Kostelec, a significant decrease of K_{avail} was observed for all treatments between 2010 and 2013 ($P < 0.001$). Since 2011, K_{avail} of treatments C and E was lower than that of other treatments ($P < 0.05$). In 2013, a slight increase of K_{avail} was observed for treatment E compared to the contents in 2012 ($P = 0.01$).

T a b l e 4

Overview of crop yields at experimental sites in main product (MP) and by-product (BP) [t/ha]. Moisture: cereals / rapeseed / pea 14%; sugar beet / potato actual moisture at harvest; alfalfa and clover – yields in dry matter. In brackets – standard deviations.

Site		2010		2011					2012		2013
		ww	alf / clo*	ww	pea	sb / pot*	rap / mus	alf / clo*	bar	alf / clo*	ww
Ivanovice	MP	6.4 (1.0)	2.7 (0.6)	7.4 (0.5)	4.0 (0.7)	61 (21)	0.9 (0.2)	7.4 (0.5)	3.5 (0.4)	3.2 (0.2)	7.6 (0.4)
	BP	4.0 (0.7)	–	7.9 (0.8)	3.5 (0.6)	31	2.2 (0.4)	–	3.9 (0.6)	–	9.3 (0.6)
Hněvčeves	MP	10.2 (0.5)	3.3 (0.5)	11.1 (0.3)	4.5 (0.1)	89 (9.7)	1.0 (0.1)	15.9 (2.1)	6.3 (0.5)	18.3 (1.1)	6.6 (1.4)
	BP	11.9 (0.9)	–	8.4 (0.5)	4.1 (0.1)	45	2.0 (0.4)	–	6.4 (1.7)	–	7.4 (1.6)
Kostelec	MP	8.3 (0.5)	4.0 (0.5)	7.0 (0.8)	2.6 (0.5)	99 (6.2)	3.3 (0.1)	9.1 (1.9)	6.6 (0.7)	9.3 (0.3)	10.6 (0.8)
	BP	4.4 (0.2)	–	3.1 (0.2)	2.3 (0.4)	50	4.2 (0.2)	–	3.0 (0.3)	–	9.1 (0.7)
Prague	MP	7.6 (0.5)	5.7 (1.0)	5.6 (0.2)	2.9 (0.0)	82 (11.5)	0.7 (0.1)	19.7 (1.7)	3.2 (0.5)	15.3 (1.8)	10.7 (0.7)
	BP	3.8 (0.4)	–	2.1 (0.3)	2.6 (0.1)	41	2.0 (0.3)	–	2.1 (0.3)	–	5.4 (0.5)
Pernolec	MP	2.2 (0.5)	1.0 (0.2)	2.9 (0.2)	2.7 (0.2)	26.7 (0.7)	1.4 (0.1)	13.2 (0.4)	4.1 (0.4)	11.4 (0.2)	4.1 (1.0)
	BP	1.7 (0.4)	–	2.3 (0.2)	2.5 (0.3)	–	–	–	2.2 (0.2)	–	3.2 (0.8)
Vysoké	MP	8.4 (0.3)	3.1 (0.4)	6.3 (0.3)	6.3 (0.3)	43 (1.0)	4.8 (0.4)	12.0 (0.7)	5.9 (0.3)	9.8 (0.8)	6.3 (0.4)
	BP	8.5 (0.3)	–	8.3 (0.3)	–	–	–	–	6.2 (0.3)	–	6.4 (0.4)
Average	MP	7.2	3.3	6.7	3.3	83 / 35	1.5	12.9	4.9	11.2	7.7
	BP	5.7	–	5.4	3.0	44 / –	2.6	–	4.0	–	6.8

ww – winter wheat (triticale was used instead of winter wheat in all cases at Vysoké nad Jizerou), alf / clo – alfalfa / clover, sb / pot – sugar beet / potato, rap / mus – rapeseed / mustard, bar – spring barley
* – latter crop was used in Pernolec and Vysoké nad Jizerou

In Vysoké, the courses of K_{avail} were very similar to those in Kostelec. A significant decrease of K_{avail} was observed for all treatments between 2010 and 2013 ($P < 0.001$). K_{avail} of treatment E was significantly lower than that of other treatments in 2011 and 2012 ($P < 0.05$). In 2013, however, there were no significant differences among the treatments because of the increase of K_{avail} in treatment E.

Trends of K_{avail} at sites of higher K_{fix} (Prague, Ivanovice and Pernolec) were not so straightforward (Table 6). In 2013, there were no significant differences between treatments at these sites, with exception of significantly higher K_{avail} of treatment F compared to treatments A, B and C in Ivanovice ($P < 0.05$). This treatment in Ivanovice had the highest K_{avail} level during the whole experiment.

Soil fixed potassium

In general, K_{fix} differences between treatments were less significant than those of K_{avail} (Figure 3). Partially it was due to the higher variability of K_{fix}

T a b l e 5

Potassium uptake at experimental sites [kg/ha/year] by main product (MP), by-product (BP) and total biomass (TB). In brackets – standard deviations.

Site		2010		2011					2012		2013
		ww	alf / clo*	ww	pea	sb / pot*	rap / mus	alf / clo*	bar	alf / clo*	ww
Ivanovice	MP	19 (3)	57 (11)	25 (2)	31 (6)	66 (16)	5 (1)	131 (11)	13 (2)	58 (4)	27 (1)
	BP	18 (1)	–	35 (6)	30 (5)	154	36 (6)	–	17 (3)	–	41 (3)
Hněvčeves	MP	32 (2)	70 (3)	34 (2)	34 (2)	192 (22)	6 (1)	325 (53)	23 (2)	365 (23)	24 (5)
	BP	67 (5)	–	39 (3)	32 (4)	223	43 (5)	–	35 (9)	–	45 (10)
Kostelec	MP	26 (2)	87 (4)	24 (3)	21 (4)	135 (15)	5 (1)	211 (32)	24 (2)	220 (8)	39 (3)
	BP	21 (2)	–	10 (1)	19 (4)	248	32 (3)	–	12 (2)	–	43 (3)
Prague	MP	24 (2)	67 (10)	19 (1)	22 (1)	111 (14)	6 (1)	262 (23)	12 (2)	202 (24)	38 (2)
	BP	22 (3)	–	11 (2)	21 (0)	205	31 (4)	–	12 (2)	–	32 (0)
Pernolec	MP	7 (2)	21 (1)	12 (1)	25 (2)	113 (3)	12 (1)	305 (21)	18 (2)	258 (5)	16 (4)
	BP	8 (2)	–	19 (2)	20 (2)	102 c	–	–	11 (1)	–	15 (4)
Vysoké	MP	31 (1)	70 (15)	30 (2)	116 (10)	189 (11)	50 (9)	309 (34)	28 (1)	248 (21)	27 (2)
	BP	97 (3)	–	75 (8)	–	171 c	–	×	31 (2)	–	73 (5)
Average	MP	23	73	23	30	144	6	259	21	229	29
	BP	35		29	27	183	36		20		37
	TB	59	73	53	57	327	42	259	41	229	66

ww – winter wheat (triticale was used instead of winter wheat in all cases at Vysoké nad Jizerou),
alf / clo – alfalfa / clover, sb / pot – sugar beet / potato, rap/mus – rapeseed / mustard, bar – spring barley
* – latter crop was used in Pernolec and Vysoké nad Jizerou, c – calculated

contents within replications. In Hněvčeves, Vysoké and Kostelec, alfalfa / clover cropping (treatment E) led to the lowest K_{fix}, whereas crop sequence with cereals (treatment A) had the highest K_{fix}. In Hněvčeves, K_{fix} decreased markedly in all treatments during the experiment (P < 0.001), but this trend was not recorded at other sites.

In Prague and Pernolec, no significant differences of K_{fix} were indicated within the whole experimental period. In Ivanovice, significant differences were recognized only in 2012 between K_{fix} of treatment D and treatments B, E and F (P < 0.05), but this difference did not appear in other years.

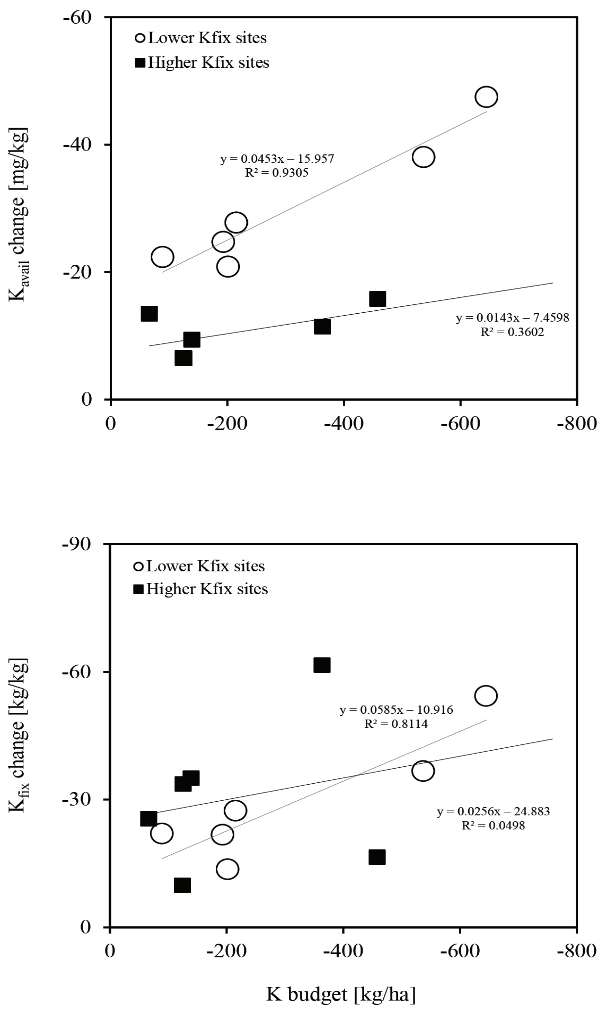

Figure 4. Relation between 3-year budget and change of available and fixed K contents for lower K_{fix} sites (sites of fixed K_{fix} < 1,000 mg K/kg – Vysoké, Kostelec, Hněvčeves) and higher K_{fix} sites (K_{fix} > 1,000 mg K/kg – Ruzyně, Pernolec, Ivanovice)

K budget vs. soil K

A clear trend was found between total K budget and change in soil K_{avail} within 2010 and 2013 for sites of lower K_{fix} (Vysoké, Kostelec, Hněvčeves, P = 0.002), but no trend was found for sites of higher K_{fix} (Figure 4). The same holds also for the change of K_{fix}, which is significant only for sites of lower K_{fix} (P = 0.007). As can be seen from the steepness of the K_{avail} and K_{fix} regression lines, a decrease of K_{fix} per a K budget unit was slightly but insignificantly higher (56%) than the decrease of K_{avail} (44% of the decrease of both forms).

DISCUSSION

K budgets

The highest K uptake was recorded for sugar beet, which is known for its high K demand and high K content in leaves (on average 4.5% K in dry matter; Neuberg *et al.* 1980). Potato represents also a large sink of soil K, as majority of this element is present in tubers. Sugar beet can utilize less-available forms of K (Vaněk *et al.* 2007). This was confirmed only by K_{fix} trend from Kostelec (Figure 3).

In several European long-term fertilisation experiments, annual K budgets in conventional agricultural systems including sugar beet and potato are in the range from –23 to –75 kg K/ha (Blake *et al.* 1999; Andrist-Rangel *et al.* 2007). Our K budget for treatment C is therefore lower; for a 4-year period it is –124 kg K/ha/year. It is due to harvesting all by-products, as the intent of the experiment was to keep K budget as low as possible. Leaves of sugar beet are however usually not harvested in recent agricultural practice. They represent an important K source and thus compensate high K offtake; Onderka *et al.* (2001) reported that by post-harvest incorporation of sugar beet leaves, 148 kg K/ha was applied back to soil.

Permanent grasslands are also known for their highly negative K budget, which is given by high K concentration in grass/clover biomass (1.2–2.7% in dry matter; Öborn *et al.* 2005). Asdal and Bakken (1999) reported that total K budgets were in the range from –228 to –527 kg K/ha in a 6-year crop rotation with 50% of clover

Table 6

Available (K_{avail}) and fixed (K_{fix}) potassium contents [mg/kg] during the experiment at sites of higher fixed K. In brackets – standard deviations.

Site	Treatment	K_{avail}				K_{fix}			
		2010	2011	2012	2013	2010	2011	2012	2013
Prague	A	181 (7)	186 (8)	168 (5)	175 (7)	991 (22)	1,009 (20)	1,000 (17)	1,032 (75)
	C	186 (2)	148 (4)	165 (2)	178 (8)	1,015 (21)	992 (26)	1,014 (7)	997 (66)
	E	170 (10)	156 (11)	155 (3)	158 (23)	994 (33)	979 (41)	986 (23)	1,008 (24)
	F	190 (13)	176 (15)	181 (13)	179 (9)	1,003 (24)	1,007 (30)	1,018 (22)	1,008 (41)
Ivanovice	A	162 (7)	168 (8)	160 (14)	153 (5)	1,075 (14)	1,067 (14)	1,024 (33)	1,047 (3)
	C	159 (3)	179 (13)	156 (10)	147 (4)	1,087 (15)	1,076 (18)	1,027 (17)	1,057 (9)
	E	177 (9)	180 (18)	188 (22)	157 (6)	1,069 (21)	1,059 (21)	992 (35)	1,060 (48)
	F	189 (17)	193 (17)	207 (28)	180 (17)	1,083 (32)	1,089 (31)	1,013 (11)	1,036 (5)
Pernolec	A	96 (11)	120 (6)	78 (8)	90 (7)	1,475 (96)	1,463 (88)	1,451 (96)	1,432 (64)
	C	85 (7)	99 (5)	76 (7)	81 (4)	1,393 (175)	1,370 (170)	1,347 (235)	1,312 (167)
	E	109 (15)	106 (14)	111 (33)	94 (17)	1,376 (209)	1,373 (224)	1,371 (269)	1,322 (289)
	F	105 (7)	104 (14)	106 (11)	86 (7)	1,338 (177)	1,343 (174)	1,347 (260)	1,303 (248)

ley; maximum annual K uptake reached –175 kg K/ha in the first year of clover. Our results are even higher; in Hněvčeves the K offtake by alfalfa reached 365 kg K/ha in 2012. Such high offtake is not unrealistic. Øgaard and Krogstad (2005) reported that in non-K-fertilised soils in Norway, annual K offtake in the first year of grassland exceeded 300 kg K/ha in some cases.

Soil K pools

Our results show that K_{avail} and K_{fix} dynamics depends on the K_{fix} level, as majority of significant differences appeared for sites of lower K_{fix} content (Vysoké, Kostelec and Hněvčeves). Vopěnka and Macháček (1985) found that K_{fix} level have an influence on relation between K_{avail} and K budget. In soils of K_{fix} higher than 1200 mg K/kg, K_{avail} increased even when the budget was negative; in soils of K_{fix} lower than 600 mg K/kg, K_{avail} usually decreased even when the budget was positive. This can explain why almost no significant differences in K_{avail} were found in Prague, Ivanovice and Pernolec. Possible differences might be also masked by high K_{fix} variability in soils of Prague and Pernolec.

Øgaard and Hansen (2010) studied changes of K_{avail} and K_{fix} in 6 grassland fertilisation experiments without K fertilisation. They found large differences between the sites in K uptake from K_{fix}. In all sites, K_{avail} contributed to total K uptake (40–183 kg K/ha) by less than 40 kg K/ha and majority of K uptake was fulfilled from K_{fix}. This was observed in Hněvčeves, where K_{fix} decreased rapidly, whereas K_{avail} remained without significant changes for 5 of 6 treatments. Øgaard and Krogstad (2005) found that K uptake from K_{fix} pool ('interlayer K') during 3 years of grass cropping increased with the percentage of clay in the soil consisting of 1 to 34% clay. For soils containing >12% clay, K_{fix} release covered 43% of the K uptake. In our data, the relation with clay content was not observed, which might be due to a narrower range of clay content in soil.

CONCLUSION

Negative nutrient budget represents potential risk for intensive agricultural systems. We showed that K budget can be very negative in case of K demanding crops. However, by-products are often not harvested in common agricultural praxis, as well as sub-optimal K application rates replace a part of removed soil K. According to the actual data about K inputs and outputs in the agricultural soils of the Czech Republic, a reasonable estimate of average K budget is in the range from about –50 kg K/ha/year (main and by-product harvested) to about –20 kg K/ha/year (only main product harvested).

Therefore, based on the linear regressions found, potentially available K reserve ($K_{avail} + K_{fix}$) decreases annually approximately by from 17 to 32 mg K/kg in topsoils with K_{fix} <1,000 mg K/kg. Approximately half of this depletion originates from K_{fix}. Therefore, by simple calculation, available K reserve can be exhausted within 3 to 4 decades in soils of lower K_{fix} content. However, such fast 'potassium mining' is not realistic because the plant available pool is continuously replenished from structural K by weathering of soil minerals.

With respect to K availability, susceptible agricultural soils are soils of low K_{fix} used for production of crops with high K offtake, e.g. forage, potato and sugar beet. In these soils, K_{fix} dynamics should be monitored for preventing the risk of decreased K availability, which can result in yield or quality drop, e.g. in case of a drought stress.

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REFERENCES

ANDRIST-RANGEL, Y. – EDWARDS, A.C. – HILLIER, S. – ÖBORN, I. 2007. Long-term dynamic of organic and conventional mixed cropping systems as related to management and soil properties. In *Agriculture, Ecosystems and Environment*, vol. *122*, pp. 413–426. DOI: 10.1016/j.agee.2007.02.007.

ANONYMOUS 2013. *Zemědělství 2012 [Agriculture 2012]*. Prague: Ministry of Agriculture of the Czech Republic. 126 pp. ISBN 978-80-7434-111-3.

ASDAL, Å. – BAKKEN, A. 1999. Nutrient balances and yields during conversion to organic farming in two crop rotation systems. In OLESEN, J.E. – ELTUN, R. – GOODING, M.J. – JENSEN, E.S. – KÖPKE U. (Eds.). *Designing and testing crop rotations for organic farming*. Foulum: DARCOF, pp. 125–134.

BLAKE, L. – MERCIK, S. – KOERSCHENS, M. – GOULDING, K.W.T. – STEMPEN, S. – WEIGEL, A. – POULTON, P.R. – POWLSON, D.S. 1999. Potassium content in soil, uptake in plants and the potassium balance in three European long-term field experiments. In *Plant and Soil*, vol. *216*, pp. 1–14. DOI:10.1023/A:1004730023746.

EDMEADES, D.C. – MORTON, J.D. – WALLER, J.E. – METHERELL, A.K. – ROBERTS, A.H.C. – CAREY P. 2014. The diagnosis and correction of potassium deficiency in New Zealand pastoral soils: a review. In *New Zealand Journal of Agricultural Research*, vol. *53*, pp. 151–173. DOI:10.1080/00288233.2010.482954.

GRZEBISZ, W. – DIATTA, J. – HARDTER, R. – CYNA K. 2010. Fertilizer consumption patterns in Central European countries – effect of actual yield development trends in 1986–2005 years – a comparative study of the Czech Republic and Poland. In *Journal of Central European Agriculture*, vol. *11*, no.1, pp.73–82. DOI:10.5513/JCEA01/11.1.809.

HEJCMAN, M. – BERKOVÁ, M. – KUNZOVÁ, E. 2013. Effect of long-term fertilizer application on yield and concentrations of elements (N, P, K, Ca, Mg, As, Cd, Cu, Cr, Fe, Mn, Ni, Pb, Zn) in grain of spring barley. In *Plant, Soil and Environment*, vol. *59*, no. 7, pp. 329–334.

HUANG, P.M. 2005. Chemistry of potassium in soils. In TABATABAI, M.A. – SPARKS, D.L. (Eds.). *Chemical processes in soils*. Madison: SSSA, pp. 227–292. ISBN 0-89118-843-6.

KLÍR, J. – KUNZOVÁ, E. – ČERMÁK, P. 2008. *Rámcová metodika výživy rostlin a hnojení [Frame methodology of plant nutrition and fertilization]*. Prague: Crop Research Institute, 48 pp. ISBN 978-8087011-61-4.

MADARAS, M. – KOUBOVÁ, M. – SMATANOVÁ, M. 2014. Long-term effect of low potassium fertilization on its soil fractions. In *Plant, Soil and Environment,* vol. *60*, 2014, no. 8, pp. 358–363.

MARTIN, H.W. – SPARKS, D.L. 1985. On the behaviour of nonexchangeable potassium in soils. In *Communications in soil science and plant analyses*, vol. *16*, pp.133–162. DOI:10.1080/00103628509367593.

MEHLICH, A. 1984. Mehlich-3 soil test extractant: a modification of Mehlich-2 extractant. In *Communications in soil science and plant analyses,* vol. *15*, pp. 1409–1416. DOI:10.1080/00103628409367568.

MORITSUKA, N. – YANAI, J. – KOSAKI, T. 2004. Possible processes releasing nonexchangeable potassium from the rhizosphere of maize. In *Plant and Soil*, vol. *258*, pp. 261–268. DOI:10.1023/B:PLSO.0000016556.79278.7f.

NEUBERG, J. 1980. *Komplexní metodika výživy rostlin [The Complex Methodology of Plant Nutrition]*. Prague: UVTIZ, 327 pp.

ÖBORN, I. – ANDRIST-RANGEL, Y. – ASKEKAARD, M. – GRANT, C.A. – WATSON, C.A. – EDWARDS, A.C. 2005. Critical aspects of potassium management in agricultural systems. In *Soil Use and Management*, vol. *21*, no.1, pp. 102–112. DOI:10.1111/j.1475-2743.2005.tb00114.x.

ØGAARD, A.F. – HANSEN, S. 2010. Potassium uptake and requirement in organic grassland farming. In *Nutrient Cycling in Agroecosystems*, vol. 87, no. 1, pp.137–149. DOI:10.1007/s10705-009-9320-5.

ØGAARD, A.F. – KROGSTAD, T. 2005. Release of interlayer potassium in Norwegian grassland soils. In *Journal of Plant Nutrition and Soil Science*, vol. *168*, pp. 80–88. DOI:10.1002/jpln.200421454.

ONDERKA, M. – MÍŠA, P. – PROKEŠ, J. – ZIMOLKA, J. – RICHTER, R. – POKORNÝ, E. 2001. Vliv zaorávání chrástu cukrovky na kvalitu sladovnického ječmene [Influence of ploughing in sugar beet leaves on the quality of malt barley]. In *Úroda*, vol. *47*, no.1, pp. 6–7.

REES, G.L. – PETTYGROVEA, G.S. – SOUTHARDA, R.J. 2014. Estimating plant-available potassium in potassium-fixing soils. In *Communications in Soil Science and Plant Analysis*, vol. *44*, pp. 741–748. DOI:10.1080/00103624.2013.748129.

RENGEL, Z. – DAMON, P.M. 2008. Crops and genotypes differ in efficiency of potassium uptake and use. In *Physiologia Plantarum*, vol. *133*, pp. 624–636. DOI:10.1111/j.1399-3054.2008.01079.x.

SCHEFFER, F. – SCHACHTSCHABEL P. 1976. *Lehrbuch der Bodenkunde*. Stuttgart: Ferdinand Enke Verlag, 394 pp. ISBN 3-432-84779-3.

TORMA, S. 1999. *Draslík – dôležitá živina v pôde a v rastline [Importance of potassium for soils and plants]*. Bratislava: VÚPOP, 69 p. ISBN 80-85361-51-5.

VANĚK, V. –BALÍK, J. – PAVLÍKOVÁ, D. – TLUSTOŠ, P. 2007. *Výživa polních a zahradních plodin [Nutrition of field and garden plants]*. Prague: Profi-Press, pp. 176. ISBN 976-80-86726-25-0.

VOPĚNKA, L. – MACHÁČEK, V. 1985. Bilanční sledování stavu zásobenosti půd draslíkem [Study of the balance of potassium reserve in the soil]. In *Rostlinná Výroba*, vol. *31*, no. 9, pp. 905–912.

ZÖRB, C. – SENBAYRAM, M. – PEITER, E. 2014. Potassium in agriculture – Status and perspectives. In *Journal of Plant Physiology*, vol. *171*, no. 9, pp. 656–669. DOI:10.1016/j.jplph.2013.08.008.

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