Long-term effect of low potassium fertilization on its soil fractions

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ABSTRACT

In the Czech Republic, negative potassium (K) budget in agricultural soils is caused by non-fertilization by K and by a decline of manure application. We investigated soil available, fixed (acid-extractable, K_{fix}) and structural K pools in the field trial with graduated K application rate, established in 1972 at 8 sites of different climate and soils. The content of K-bearing minerals was evaluated on semi-quantitative scale by XRD diffraction. K-feldspars were a dominant source of structural K. Total soil K consisted of 1.7–7.1% of fixed K, which was in a positive relation to mixed-layer phyllosilicates. Differences in available K in treatments with K budget lower than –30 kg K/ha/year were small compared to those of fixed K. In control treatments, calculated average depletion of available K was –18 kg K/ha/year and the average depletion of fixed K was –12 kg K/ha/year; however at sites of higher altitude fixed K depletion prevailed. Fixed K accounted for 6–31% of the K budget. In negative K budget, monitoring of K_{fix} is advisable to avoid fertility loss of soil with low K supplying capacity.

Keywords: plant nutrition; soil mineralogy; X-ray diffraction; non-exchangeable potassium; long-term experiments

Potassium (K) is required by crop plants in large quantities as its concentration in plant biomass is at the second place just after the nitrogen (Syers 1998). The actual average annual K application rate in the Czech Republic is as low as 5.4 kg/ha of K in mineral fertilizers and 18 kg/ha in manures (Anonymous 2013), whereas overall outputs are 71 kg/ha on average (Klír et al. 2008). Since 1989, a highly negative K budget became standard for current agricultural practice in the Czech Republic, especially on farms without animals. The lack of K fertilization leads to lower K concentrations in plant tissues (Hejcman et al. 2013), which may result in higher plant susceptibility to low temperature, drought and salinity stress (Cakmak 2005). In many world areas, K deficiency leads to progressive decline in soil fertility and K status is recognized as an important factor restricting crop yields (Römheld and Kirkby 2010).

Mineral soils contain from 0.4 to 30 g/kg K, which is distributed between K available to plants (K_{avail}; i.e. solution K and exchangeable K); fixed K (K_{fix}) and structural K (K_{struct}) in K-bearing feldspars and layer silicates (Huang 2005). Analysis of K_{avail} is standard for assessment of nutritional status of soils; however, a release of K_{fix} to the available forms takes place when K_{avail} is decreased by plant removal (Moritsuka et al. 2004), microbial activity and leaching (Martin and Sparks 1985). The measurement of K_{fix} is therefore often suggested to improve prediction of real availability of K to plants (Rees et al. 2013, Edmeades et al. 2014).

Knowledge about effects of non-fertilization on soil K fractions or soil K bearing minerals was usually gathered from one-site long-term experiments (Blake et al. 1999, Scherer et al. 2003, Barré et al. 2008, Lukin 2012, Hejcman et al. 2013). On the other hand, many studies relating K reserves to

Supported by the Ministry of Agriculture of the Czech Republic, Projects No. QI91C118 and RO0414.

soils of different mineralogy (Andrist-Rangel et al. 2010, Sarkar et al. 2013) do not include information about long-term K budget. In our research, we use the data from the experiment realized at eight sites covering a variety of soils and climatic conditions of arable soils of the Czech Republic, which allowed us to study soil and environmental interferences together with the influences of agricultural management. The aim of our research was to investigate the extent of soil K changes in conditions of negative K budget and how it is influenced by soil mineralogy and site characteristics.

MATERIAL AND METHODS

Experimental design. The long-term experiment (LTE) was established within the years 1972 and 1983 by the Central Institute for Supervising and Testing in Agriculture (CISTA). For this study, we selected two sites in warm regions (sugar beet growing region – SBGR) and six in moderately-warm region (potato growing region – PGR; Table 1). Until 1990, 9-year crop rotation was applied; afterwards crops were grown in 8-year crop rotation: 1. oat – alfalfa (SBGR)/oat – clover (PGR); 2. alfalfa/clover; 3. winter wheat; 4. potato; 5. winter wheat; 6. spring barley; 7. sugar beet (SBGR)/potato (PGR); 8. spring barley.

At each site, treatments were replicated 6-times. The trial included four treatments $N_2P_2K_{0,1,2,3}$ of graduated K mineral application rates: 0, 51, 81 and 119 kg K/ha/year (as KCl) in SBGR and 0, 57, 90 and 131 kg K/ha/year in PGR (in text referred to as K0–K3). Farmyard manure (FYM) was applied every 4 years at a rate of 40 t/ha (as fresh matter). Farmyard manure increased mean annual K input by 35 kg K/ha. Average N application rate was 112 kg N/ha/year and those of P 42 kg P/ha/year. Crop yields and K contents in main and side products were recorded every year by CISTA. Information about simple nutrient budget calculated as input of fertilizers minus above-ground crop uptake was taken from the report of Klement et al. (2012).

Soil sampling and analyses. Soil samples of plough horizon (depth of 0–25 cm) were taken after harvest 2010, dried at room temperature and sieved through 2 mm mesh. Mixed samples consisting of 6 subsamples (plot replications) were used for further analyses. K_{avail} was extracted by 1 mol/L ammonium acetate (1:10 w/v). K_{fix} was calculated as K extracted by 1 mol/L HCl (1:10 w/v, incubation 20 h at 50°C) subtracted by K_{avail}. *Aqua regia* extractable pool ($K_{aq.r.}$) was calculated as K extracted by *aqua regia* subtracted by K_{avail} and K_{fix}. Total K was analyzed after HF-$HClO_4$ digestion. Structural K was calculated as a difference between total K and K in *aqua regia* extract. Each soil sample was extracted twice and each extract was analyzed twice by ICP EOS (Thermo Jarrel Ash, Trace Scan, Franklin, USA). Organic carbon (C_{ox}) was analyzed after wet combustion. For soil texture specification, sedimentation method was used (ISO 11277). Cation exchange capacity (CEC) was analyzed by $BaCl_2$ method (ISO 13536). The soil mineralogical composition was determined from soils of K0 treatment on the basis of

Table 1. Characteristics of experimental sites and soils

Location	Establishment of the trial	Altitude (m)	Region	Mean annual precipitation (mm)	Mean annual air temperature (°C)	Soil type	C_{ox} (%)	Texture (%) < 0.001 (mm)	< 0.01 (mm)	< 0.05 (mm)	CEC (mmol₊/100 g)	Exchangeable Ca+Mg (mmol₊/100 g)
Uherský Ostroh	1972	196	SB	551	9.2	Luvisol	1.2	19.4	28.7	50.8	13.7	13.7
Žatec	1972	247	SB	451	8.3	Chernozem	2.1	26.8	45.4	75.6	26.8	25.6
Chrastava	1977	345	P	798	7.1	Luvisol	1.4	11.3	29.4	90.5	13.8	12.2
Staňkov	1981	370	P	511	7.8	Luvisol	1.3	12.5	27.9	67.1	10.9	10.9
Jaroměřice	1975	425	P	535	7.5	Luvisol	1.3	19.1	39.4	79.3	15.3	12.2
Svitavy	1981	460	P	624	6.5	Luvisol	1.1	9.8	24.4	47.6	11.0	11.0
Lípa	1974	505	P	632	7.7	Cambisol	1.4	7.5	31.6	67.7	13.4	8.9
Vysoká	1983	595	P	655	7.4	Stagnosol	1.6	9.8	32.8	59.1	14.8	12.9

Region – growing region of sugar beet (SB) or potato (P); CEC – cation exchange capacity

Table 2. Contents of K fractions (mg/kg) in soils at the beginning of the trial and in 2010 (treatments K0 and K3)

Location	K_{avail} at the beginning of the trial	Soil K pools				Total K
		K_{avail}	K_{fix}	$K_{aq.r.}$	K_{struct}	
Uherský Ostroh	271	232–338	885–950	3700–4500	9600	15 000
Žatec	238	149–378	657–754	4500–4900	9900	15 600
Chrastava	191	88–186	316–347	2300–2700	15 400	18 400
Staňkov	126	88–274	733–770	3200–2900	14 100	18 000
Jaroměřice	195	173–304	1313–1435	5100–5400	13 800	20 700
Svitavy	230	95–176	339–400	2100–2300	12 400	15 400
Lípa	147	78–172	783–939	3700–3900	16 300	21 000
Vysoká	200	98–198	452–536	2700–2500	9300	13 400

K0 – 0 kg K/ha/year; K3 – 131 kg K/ha/year; K_{avail} – K available to plants; K_{fix} – fixed K; $K_{aq.r.}$ – *Aqua regia* extractable pool; K_{struct} – structural K

XRD patterns, which were obtained using CuK radiation with the powder difractometer X´Pert System Philips with a graphite monochromator (Almelo, the Netherlands). The relative presence of main soil minerals was evaluated on semi-quantitative 5-point scale in a range from the limit of detectability (+) to dominant mineral (+++++). Statistical evaluation of the results was performed using the Statistica 10 software (Statsoft, Tulsa, USA).

RESULTS AND DISCUSSION

Soil K pools and mineralogy. Total K content in investigated soils was in the range from 13 000 to 21 000 mg/kg (Table 2). Total soil K comprises of 1.1% K_{avail} (0.5–2.5%), 4.3% K_{fix} (1.7–7.1%), 23% $K_{aq.r.}$ (12.8–34.2%) and 72% K_{struct} (58.5–85%). K pools and their proportions to total K were significantly related both to environmental conditions of sites and to soil properties, however these two groups of parameters were interrelated. There was a positive relationship between mean site temperature and the share of K_{avail} (P = 0.033), K_{fix} (P = 0.056) and $K_{aq.r.}$ (P = 0.049) on the total K. Soils of higher clay content had higher average K_{avail} content (P = 0.042). The content of K_{fix} was in a positive relation to mixed-layer phyllosilicates (MLP) (P = 0.015), which is due to preferential dissolution of MLP by HCl (Andrist-

Table 3. Soil mineralogical composition (relative presence: +++++ – dominant mineral; + – present at the limit of detectability)

Location	Quartz	Feldspars		Mica group	K + C	K:C	Mixed-layer phyllosilicates		A + P
		plagioclase	K-feldspar						
Uherský Ostroh	+++++	++/+++	++	+	+	K	++/+++	I/S	
Žatec	+++++	++	++	+/++	++	K	++	I/S	
Chrastava	+++++	++/+++	++/+++	++	++	C ≥ K	+/++	I/S	
Staňkov	+++++	+++	+++/++++	+/++	+/++	K > C	+/++	I/S + C/S	++
Jaroměřice	+++++	+++	+++	++/+++	++/+++	C ≥ K	++/+++	I/S	
Svitavy	+++++	+/++	++	> +	+	K ≥ C	+	I/S	
Lípa	+++++	+++	+++	++/+++	++/+++	C ≥ K	++/+++	C/S + I/S	
Vysoká	+++++	+++	+/++	++	++	K ≥ C	+/++	C/S	

C – chlorite; K – kaolinite; S – smectite; I – illite; A – amphibole; P – pyroxene

Table 4. Relation between soil K fractions and soil and site parameters for treatments with minimum (K0) and maximum (K3) K fertilization

		K_{fix}	$K_{aq.r.}$	K_{struct}	Clay content	K-feldspar	Mica-group minerals	Mixed-layer silicates	Altitude
K0	K_{avail}	ns	0.75*	ns	0.80*	ns	ns	ns	ns
	K_{fix}	–	0.73*	ns	ns	ns	ns	0.82*	ns
	K_{struct}	–	–	–	ns	0.79*	ns	ns	ns
K3	K_{avail}	ns	0.74*	ns	0.95***	ns	ns	ns	–0.75*
	K_{fix}	–	0.85**	ns	ns	ns	ns	0.83**	ns
	K_{struct}	–	–	–	ns	0.79*	ns	ns	ns

K_{avail} – K available to plants; K_{fix} – fixed K; $K_{aq.r.}$ – *Aqua regia* extractable pool; K_{struct} – structural K; ns – statistically not significant; *$P \le 0.05$; **$P \le 0.01$; ***$P \le 0.001$

Rangel et al. 2013). The share of $K_{aq.r.}$ was negatively correlated with precipitation ($P = 0.029$) and positively with the content of fine particles ($P = 0.007$), which confirmed the dependence of K fractions on soil texture (Fotyma 2007). As a result of these complex influences, soils of SBGR had higher K_{avail} and also higher proportion of K_{avail} to total K than soils of PGR.

XRD analyses showed that the dominant soil mineral is quartz. All soils contained detectable amounts of main K-bearing minerals (K-feldspar, mica and mixed-layer phyllosilicates), but in different proportions (Table 3). This variability is typical for soils derived from different parent material (Andrist-Rangel et al. 2010). Dominant source of K_{struct} in the studied soils is K-feldspar, as we found a significant positive relationship between K_{struct} and its content ($P = 0.02$), whereas there was no significant relation to mica-mineral content (Table 4). Light-texture soils tend to contain less minerals of the mica group, especially at PGR ($P = 0.042$) and they also contained less MLP ($P = 0.063$; exception of this trend was the soil of Lípa).

Soil K changes affected by unbalanced fertilization. Since the beginning of the trial, K_{avail} changed markedly depending on differentiated K input; an average decrease by 38% with respect to initial value was observed at K0 while K_{avail} increased on average by 31% at K3 (Table 2). At five sites, the highest K application rates resulted in an increase of K_{avail}. However for the other three sites, the highest K application rate was sufficient only for keeping the initial K_{avail} level (Chrastava and Vysoká) or K_{avail} decreased even at the highest rate (Svitavy). It is possible that K application rates before the LTE establishment were even higher than K3, as was speculated in a similar LTE (Madaras et al. 2010). Eventually, the land use might have been different in past; unfortunately details of the management before LTE establishment are unknown. These three sites also had K_{fix} content lower than 600 mg K_{fix}/kg. Soils of K_{fix} under this treshold tend to have decreasing K_{avail} even at positive K budget (Vopěnka and Macháček 1985). We found that the content of K_{fix} is connected with MLP content, which is known not only to release K to plants but also to fix K from fertilizer (Barré et al. 2008). Lower K_{fix} therefore indicates lower capability of soil to retain K. This can contribute to fertilizer K leaching together with highly water-permeable soil at Svitavy and increased precipitation at Chrastava.

Unbalanced fertilization induced a significant differentiation of both K_{avail} and K_{fix} with respect to treatments (Figure 1). At near-zero K budget, contents of K_{fix} in neighbour treatments K2 and K3 were approximately equal, whereas K_{avail} changed in the course of K budget surplus or shortage. At this situation, it appears that dynamics of K exchange among fertilizer, soil and crops is realized mainly through K_{avail}. However, for budgets lower than –30 kg K/ha/year, there were only minor differences of K_{avail} between neighbouring treatments as it reached the constant level, which is often observed in control plots of LTEs (Blake et al. 1999, Madaras and Lipavský 2009). At Žatec, Uherský Ostroh and Jaroměřice, K_{avail} at K0 stabilized at higher level compared to the other sites, most probably due to their higher clay content. In the situation of a negative K budget we observed a depletion of K_{fix} at all sites regardless their K_{fix} content. The lowest K_{fix} content was detected for

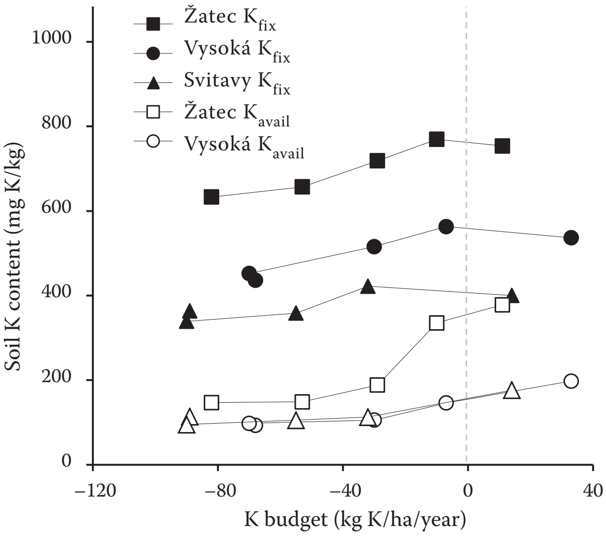

Figure 1. Relation between K budget and contents of K available to plants (K_{avail}) and fixed K (K_{fix}) at 3 sites with K application from 0 to 166 kg K/ha/year (including unfertilized control treatments)

treatments of the lowest K input, which is in accordance with the results of other LTEs (Blake et al. 1999, Scherer et al. 2003). Obviously the demand of crops for K in conditions of long-term low K input was fulfilled mainly from non-exchangeable K pool either directly (Moritsuka et al. 2004) or indirectly by a transfer through exchangeable sites.

Based on regressions between K budgets and K contents, we calculated the expected extent of K pools for the situation of zero K budget and the approximate annual depletion of K fractions for treatment K0 with respect to this zero budget (Table 5). The average depletion of K_{avail} was –18 kg K/ha/year and the average depletion of K_{fix} was –12 kg K/ha/year. At soils of higher altitude K_{fix} decrease exceeded the decrease of K_{avail}, which can be explained by a combined effect of lighter soils and a more intensive profile percolation. An efficiency of K fertilization by highly soluble K salts would be lower at these sites. However the correlation of the altitude vs. K_{avail} was not statistically significant (P = 0.099). K_{fix} decrease in a plough layer accounted for 6% to 31% of the K budget. A decrease of both forms accounted from 17% to 78%, giving evidence that substantial K uptake is realized from other soil sources, e.g. other forms and/or deeper layers (Andrist-Rangel et al. 2007). Lukin (2012) reported that crops at sandy-loamy soil in conditions of K deficit use from 31 to 41 kg/ha of non-exchangeable K.

Average change of K_{fix} per the unit of K budget (i.e. 1 kg K/ha/year) was 1.3 mg K_{fix}/kg soil. The variability of this parameter among sites appears to have relation especially to the soil texture and K_{fix} content; the multilinear regression including these two parameters explains 89% of data variation ($P < 0.001$). According to it, K_{fix} depletion per the unit of K budget is enhanced in heavier soils and in soils of low K_{fix}.

Finally we concluded that intensive crop production with unbalanced K fertilization leads to significant depletion of K_{fix}. The rate of this depletion can be larger than that of K_{avail} and it is dependent on K budget, soil and site characteristics. Even though the annual decrease of K_{fix} is relatively small compared to the extent of this K pool, it is advisable to monitor K_{fix} to avoid fertility loss in soil of low K supplying capacity.

Table 5. Calculated annual K depletion of available (ΔK_{avail}) and fixed (ΔK_{fix}) K pools for treatment K0 (assuming 25 cm plough layer and specific weight 1.4 g/cm^3)

Location	K budget for treatment K0 (kg K/ha/year)	K calculated for zero budget		Difference between K0 and contents at zero K budget		
		K_{avail}	K_{fix}	ΔK_{avail}	ΔK_{fix}	sum
		(mg/kg)		(kg/ha/year)		
Uherský Ostroh	–117	340	944	–13	–7	–20
Žatec	–53	342	758	–24	–13	–37
Chrastava	–68	353	403	–40	–13	–53
Staňkov	–80	193	761	–19	–5	–24
Jaroměřice	–68	243	1391	–10	–11	–21
Svitavy	–90	154	407	–11	–12	–23
Lípa	–68	179	940	–14	–21	–35
Vysoká	–70	156	533	–12	–17	–29

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Received on April 8, 2014
Accepted on June 12, 2014

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