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Potassium fractions in soil and simple K balance in long-term fertilising experiments

Jiří Balík, Martin Kulhánek, Jindřich Černý, Ondřej Sedlář, Pavel Suran*

Department of Agro-Environmental Chemistry and Plant Nutrition, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Prague, Czech Republic

**Corresponding author: balik@af.czu.cz*

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Abstract: Experiments were used to determine the potassium release from the non-exchangeable K (K_{ne}) forms that are involved in plant nutrition and which replenish the pool of available K. Long-term stationary field experiments with different fertilisation systems (organic: farmyard manure, sewage sludge, straw; mineral: NPK, N) were carried out to study the potassium balance and the K content changes in the topsoil (0–30 cm) and subsoil (30–60 cm). The trials were located at three sites with different soil-climatic conditions. The following crops were rotated within the trial: potatoes (maize) – winter wheat – spring barley. All three crops were grown each year over 21 years. Positive correlations between the contents of the available K in the topsoil and the potassium balance (K inputs – K outputs) were observed. There were no statistically significant differences among the treatments. Depending on the soil properties, the ratio of non-exchangeable K (K_{ne}) was 12–37% of the values obtained via the aqua regia extraction. Depending on the site, the amount released from the K_{ne} forms to the available K form was 46–69 kg K/ha/ year. The use of K from the farmyard manure varied from 7.4% up to 25%. Due to the low K content in the sewage sludge, the long-term fertilisation with sludge may only lead to the depletion of the available K in the soil, similar to the sole N mineral fertilisation.

Keywords: exchangeable and non-exchangeable K; farmyard manure; mineral fertilisation; sewage sludge; straw

The potassium content in the plant biomass and its uptake at harvest is almost the same as that of nitrogen. As shown in statistical evaluations for the Czech Republic (CR), there is extensive use of nitrogen fertilisation, while there has been a negative potassium balance in plant production for the last 30 years (Madaras et al. 2012). The average annual K application rate in the Czech Republic is as low as 11.2 kg/ha of K in mineral fertilisers and 22.0 kg/ha in organic fertilisers (Anonymous 2016), whereas the overall output is 71 kg/ha on average (Klír et al. 2008). The functioning of such a deficit system is probably possible only due to the residual effect of the previously applied potassium (Csatho 2005) or to the release of potassium from less mobile forms. Madaras et al. (2010) determined the K-stabilising application rate (K-SAR), i.e., the potassium dose necessary for a stable level of available K in the soil, based on soil properties and environmental factors and reported K-SAR (specific absorption rate) values in the range of 84–506 kg K/ha. Slightly different results in the conditions of the CR were reported by Macháček et al. (2001). For the beet production region with warmer and drier climates, K-SAR was 33–55 kg K/ha/year, while for a potato production region with a colder and wetter climate, it was 67–83 kg K/ha/year. An important factor in determining K-SAR is to optimally set the levels of the available K (K_{avail}) and crop yields. This level may be extremely low in some cases. Stabilised K_{avail} in long-term trials at non-fertilised sites

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was about 30 mg K/kg in Skierniewice (Poland) and 90–120 mg K/kg in Rothamsted (Blake et al. 1999). In soils with high contents of potentially available K, the level of K_{avail} may also sometimes increase at a negative balance (Khan et al. 2014). Hence, a stable content of K_{avail} in the topsoil does not necessarily mean balanced nutrition management.

Furthermore, Kitagawa et al. (2018) recommend determining the exchangeable potassium (K_{ex}), completed by the content of the non-exchangeable potassium K_{ne} (using extraction at 1 mol/L boiling HNO_3). The method of determining K_{ne} is not complicated, and its results do not significantly change over the years; it is, therefore, possible to recommend this method as a supplementary one, mainly for long-term unbalanced results.

The significantly positive correlation with the fixed ammonium ions supports the hypothesis that K_{ne} is mainly bound at the boundaries of clay minerals of the 2 : 1 types, mica and vermiculite (Brouder 2011). Kitagawa et al. (2018) stated that the clay mineral type is more important than the total content of the clay particles. Madaras et al. (2010), in their model for determining K-SAR, use the values obtained by the aqua regia extraction.

According to Reimann et al. (2003) and Andrist-Rangel (2008), the advantage of aqua regia as an extraction agent is the origin of the K, whose values are mainly related to the soil composition and are not influenced by the fertilisation history.

As shown by Holmquist et al. (2003), the weathering of the mineral phases in the soil results in a release of 3–82 kg K/ha/year, depending on the soil properties. Simonsson et al. (2007) published values of 65 to 85 kg K/ha/year released from the non-exchangeable reserves into available forms. According to Swedish estimates, the reserve of the potentially available potassium may be sufficient for about 30–100 years (Andrist-Rangel 2008). Merbach & Deubel (2007) published the results of long-term experiments in Halle, Germany, where the level of the potato yields at a site non-fertilised with K was 62% compared to the site regularly fertilised with 66 kg K/ha/year; by winter wheat, it was almost 100%.

In this context, the aim of this paper was to determine the changes in the contents of the K_{avail} and potentially available K, both in the topsoil and subsoil, using long-term stationary field experiments with different fertilisation systems. The other goal was to determine the amount of the potentially exchangeable K in the soil reserves.

MATERIAL AND METHODS

The effect of fertilisation on the potassium balance of potatoes (maize), winter wheat and spring barley was observed in long-term field trials. These trials were established in 1996 at five locations in the CR (an experimental base of the Czech University of Life Sciences Prague) with different soil-climatic conditions. Some of the results from the long-term experiments have already been published in the paper Balík et al. (2019), where the results from two sites were published only (B – 49°33'16''N; 15°21'2''E, D – 50°18'46''N 15°43'3''E). In this publication, the results originate from three completely different sites (A, C, E – Table 1) including the sewage sludge treatment and subsoil analyses.

Within the trials, three crops were rotated in the following order: potatoes (maize), winter wheat and spring barley. Because of the technical conditions of location E, potatoes as the experimental crop were replaced by silage maize. Each year, all of the crops were grown. The size of the experimental plots was 60 m^2, and the trial contained seven treatments replicated four times: 1 – no fertilisation (control); 2 – sewage sludge 44 kg K/ha/3 years (SS1); 3 – farmyard manure: A – 341 kg K/ha/3 years, C – 430 kg K/ha/3 years, E – 356 kg K/ha/3 years (FYM1); 4 – half dose of farmyard manure + N in mineral nitrogen fertiliser (FYM1/2); 5 – mineral nitrogen fertiliser 0 kg K/ha/3 years (N); 6 – NPK in mineral fertiliser 270 kg K/ha/3 years in potassium salt (NPK); 7 – spring barley straw + N in mineral nitrogen fertiliser: A – 42 kg K/ha/3 years, C – 47 kg K/ha/3years, E – 55 kg K/ha/3 years (N + St). The organic fertilisers, farmyard manure, sewage sludge and straw were always applied in autumn (October) to the potatoes (maize – site E). The whole system of fertilising is based on the uniform ratio of 330 kg N/ha/3 years (except for the control). This applies for the organic and mineral fertilisers as well.

The soil analyses were performed with air-dried soil samples (≤ 2 mm). The potassium content was determined using different extraction procedures (Table 2).

The content of the non-exchangeable potassium (K_{ne}) was calculated via subtracting the NH_4OAc result from the boiling HNO_3 value, according to Wood & DeTurk (1941).

The residual potassium content (K_{ar}) was extracted according to the ISO 11466:1995 procedure.

The concentrations of K in all the above-mentioned extracts were determined using optical emission spec-

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Table 1. Basic description of the investigated locations

Location	A	C	E
GPS coordinates	50°7'40''N 14°22'33''E	49°33'23''N 14°58'39''E	50°4'22''N 14°10'19''E
Altitude (m a.s.l.)	289	610	410
Mean annual temperature (°C)	9.1	7.7	7.7
Mean annual precipitation (mm)	495	666	493
Soil type	Haplic Chernozem	Stagnic Cambisol	Haplic Luvisol
Soil texture	loam	sandy loam	loam
Clay (%) (< 0.002 mm)	2.2	3.2	5.4
Silt (%) (0.002–0.05 mm)	71.8	37.1	68.1
Sand (%) (0.05–2 mm)	26.0	59.7	26.5
Bulk density (g/cm^3)	1.4	1.3	1.5
C_{org} (%)	1.6	1.3	1.2
pH (0.01 mol/L $CaCl_2$)	7.5	5.3	6.5
CEC ($mmol_{(+)}$/kg)	262	45	118

CEC – cation exchange capacity

troscopy with inductively-coupled plasma (ICP-OES) (Agilent Technologies, Mulgrave, Australia).

The results were assessed using an analysis of variance (ANOVA) with a Fisher LSD post-hoc test. To evaluate the obtained results, STATISTICA software (StatSoft Inc. 2015) was used.

RESULTS AND DISCUSSION

The potassium input and output balance of the individual treatments is shown in Table 3; it covers the balance over the period of 21 years. The outputs are determined from the obtained yields and K contents in the plants. The overall annual uptake (grain + straw – harvested part of the aboveground part of a cereal plant) reached 67.8 kg K/ha in wheat and 49.1 kg K/ha in barley. Within the crop rotation, the most dominant consumers were potato tubers, with an average of 148 kg K/ha/year. In maize, the uptake by the aboveground biomass was 117.6 kg K/ha. A positive balance was only recorded by the FYM1 treatment. The highest negative values were obtained by the sole N mineral fertilisation; depending on the site, they ranged from –1536 kg K/ha (73.1 kg K/ha/year) up to –1921 kg K/ha (91.5 kg K/ha/year). The use of K from FYM1 was 7.4% at site A, which was probably affected by the insufficient precipitation and high soil fertility. At the other sites, the output values were similar (25.0% site C, 24.7% site E). When using the half dose of the farmyard manure in FYM1/2, the uptake more than doubled (except for site A). Extremely high values (above 100%) by the SS1 treatment were probably affected by the low K content in the sludge, together with the high K uptake by the plants. The plants' biomass growth, especially in the root crops, was significantly positively affected by the nitrogen and the other supplemented nutrients (Černý et al. 2010), clearly showing that long-term intensive fertilisation with sewage sludge may only result in the K deprivation of the soil, similar to the sole N fertilisation. Wang (1997) compared 71 samples of sewage sludge from different countries (United

Table 2. Summary of the extraction methods for the potassium determination including the references

Extraction	w/v	Reference
Water (K_{H_2O})	1/10	Luscombe et al. (1979)
Mehlich 3 (K_{M3})	1/10	Mehlich (1984)
Ammonium acetate (NH_4OAc) (K_{ex})	1/10	Haby et al. (1990)
Boiling HNO_3	1/10	Helmke and Sparks (2000)
Residual potassium content, aqua regia (K_{ar})	1/20	ISO 11466:1995

w/v – the weight of the soil/volume of the extractant

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Table 3. The overall balance of the potassium inputs and outputs at the different locations (kg/ha) during the 21 years (1996–2017)

Location	Balance	Cont	SS1	FYM1	FYM1/2	N	NPK	N + St
	K input	0	308	2 387	1 194	0	1 890	252
A	crop uptake	1 467	1 400	1 643	1 617	1 599	1 637	1 523
	balance	–1 467	–1 092	744	–423	–1 599	253	–1 271
	K input	0	308	3 010	1 505	0	1 890	336
C	crop uptake	1 092	1 582	1 845	1 954	1 921	2 099	1 814
	balance	–1 092	–1 274	1 165	–449	–1 921	–209	–1 478
	K input	0	308	2 492	1 246	0	1 890	330
E	crop uptake	1 001	1 365	1 616	1 648	1 536	1 818	1 754
	balance	–1 001	–1 057	876	–402	–1 536	72	–1 424

Crop uptake = the main yield + straw (harvested part of the aboveground part of a cereal plant); cont – control; SS1 – sewage sludge; FYM1 – farmyard manure; FYM1/2 – half dose of farmyard manure + N in mineral nitrogen fertiliser; NPK – mineral fertiliser; N + St – spring barley straw + N in mineral nitrogen fertiliser

Kingdom, United States and Republic of South Africa). They determined that the potassium contents ranged from 0.2 to 0.7% (on average 0.3%). Antolín et al. (2005) published the average value of 0.47% K in sewage sludge. The sewage sludge used in our experiment contained 0.468% of potassium in the dry matter. Therefore, it is obvious that sewage sludge is only a poor source of potassium compared to N and P. By the NPK fertilised treatment, the use of K was significantly higher compared to that of the manure. At site C, it was more than 50%. The higher K usage by the mineral fertilisation may have been caused by the lower applied K dosage compared to the treatment with the manure and further by the regular annual fertilisation (Káš et al. 2016).

Content of available potassium (K_{avail}) and non-exchangeable potassium (K_{ne}). With all of the extraction agents used and almost at all of the sites, a significant increase in the K_{avail} content was determined by the FYM1 and NPK treatments (Table 4). By mineral N treatment, with the highest negative balance, no significant decrease in the K_{avail} content in the topsoil was recorded, although a slight tendency was apparent. Changes in the K_{avail} content showed

Table 4. The contents of K_{avail} and K_{ne} in the topsoil (0–30 cm) (mg K/kg)

Extractant	Location	Cont	SS1	FYM1	FYM1/2	N	NPK	N + St
	A	22^{b}	19^{a}	25^{b}	23^{b}	25^{b}	26^{b}	21^{b}
K_{H_2O}	C	13^{a}	12^{a}	36^{c}	21^{b}	21^{b}	42^{c}	22^{b}
	E	24^{b}	22^{b}	30^{cd}	26^{bc}	19^{a}	32^{d}	27^{c}
	A	188^{a}	184^{a}	220^{b}	285^{c}	201^{a}	232^{bc}	226^{bc}
K_{M3}	C	109^{a}	105^{a}	231^{d}	162^{bc}	107^{ab}	193^{c}	141^{b}
	E	103^{a}	106^{a}	148^{c}	130^{b}	106^{a}	160^{c}	141^{bc}
	A	239^{a}	239^{a}	277^{ab}	264^{b}	273^{b}	293^{b}	252^{ab}
K_{ex}	C	99^{a}	98^{a}	229^{c}	169^{b}	132^{b}	230^{c}	147^{b}
	E	126^{a}	134^{a}	195^{c}	159^{b}	127^{a}	196^{c}	179^{bc}
	A	$1\,354^{ab}$	$1\,355^{ab}$	$1\,321^{a}$	$1\,392^{ab}$	$1\,414^{ab}$	$1\,424^{b}$	$1\,344^{ab}$
K_{ne}	C	$2\,716^{ab}$	$2\,630^{a}$	$2\,809^{ab}$	$2\,811^{ab}$	$2\,767^{ab}$	$2\,909^{ab}$	$3\,001^{b}$
	E	$1\,035^{b}$	$1\,027^{b}$	924^{ab}	897^{ab}	805^{a}	$1\,006^{b}$	$1\,060^{b}$

K_{avail} – the available potassium (K_{H_2O}; K_{M3}; K_{ex}); K_{ne} – the non–exchangeable potassium; cont – control; SS1 – sewage sludge; FYM1 – farmyard manure; FYM1/2 – half dose of farmyard manure + N in mineral nitrogen fertiliser; NPK – mineral fertiliser; N + St – spring barley straw + N in mineral nitrogen fertiliser; values followed by the same letter are not significantly different ($P < 0.05$) between the experimental plots

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a significant correlation with the K balance. For the investigated extraction agents, the linear regression equations were calculated as follows:

Water extract: $y = 0.0057x + 29.6$ ($R^2 = 0.44$),

Mehlich 3: $y = 0.0324x + 196$ ($R^2 = 0.341$),

NH_4OAc: $y = 0.368x + 217$ ($R^2 = 0.342$),

where:
y – the K_{avail} content,
x – the balance values.

No significant correlations with the K uptake at harvest were determined. Similarly, Jouany et al. (1996) reported a linear relationship between the K_{ex} content and K balance.

For a more objective evaluation of the K_{ex} content, it is possible to convert the values to the relative potassium saturation of the sorption complex (Table 5). Considering the extremely low cation exchange capacity (CEC) at site C, the content of K is almost 10% of the CEC, even with the unfertilised treatment; with the FYM treatment, it is almost 17%. These values well document the oversaturation of the sorption complex with the potassium at this site. Vaněk et al. (2012) recommend the saturation of the sorption complex of K from 5% to a maximum of 7% for soils that have low CEC values, similar to site C. This is also indirectly proved by the high K content in the plants (not published yet). At other sites, the CEC saturation corresponded to the soil texture and type (A – 2.5%, E – 3.5%). This is in agreement with the results published by Vaněk et al. (2012), who reported an optimal K saturation of the sorption complex for the soils in the CR of 2.5–5%, based on the soil type.

Table 5. The potassium saturation in the cation exchange capacity (%)

Treatment	Location		
	A	B	C
Cont	2.35	9.69	2.74
SS1	2.34	9.74	2.91
FYM 1	2.41	16.87	4.24
FYM 1/2	2.58	12.48	3.46
N	2.67	9.57	2.76
NPK	2.87	11.74	4.26
N + St	2.47	10.20	3.91
Average	2.53	11.47	3.47

Cont – control; SS1 – sewage sludge; FYM1 – farmyard manure; FYM1/2 – half dose of farmyard manure + N in mineral nitrogen fertiliser; NPK – mineral fertiliser; N + St – spring barley straw + N in mineral nitrogen fertiliser

The content of the available K was also determined in the subsoil (30–60 cm). There were no statistically significant differences among the treatments; hence, only the average values for the individual sites are presented (Table 6). The relatively short time of the experiments (21 years), the low to medium intensity of the K fertilisation as well as the higher variability in the subsoils compared to the topsoil may be the reason for the absence of any statistical differences in the K_{avail} in the subsoil (Mallarino & Ul-Haq 1997).

The results obtained in these experiments show that the subsoil contains significantly less K_{avail} than the topsoil. At water extraction, it was, on average, 78% compared to the topsoil K and 79% by the exchangeable potassium (K_{ex}). This was affected by the significantly decreased total cation capacity in the subsoil, which is related to the lower contents of the organic matter and mineral colloids. Similarly, Yadav et al. (2018) also observed a significant decrease in the water-extractable K and exchangeable K (K_{ex}) in the subsoil (25–55 cm) compared to the topsoil (0–25 cm). An opposite trend was measured at the non-exchangeable (K_{ne}). The concentration of K_{ne} increased with the depth indicating the relatively less mining of this form of K by the plant roots from lower layers. Also, Simonsson et al. (2007) reported the highest content of K_{ex} in the 0–20 cm layer, which decreased significantly in the subsoil.

The calculation of the K content in the subsoil to the volumetric weight at the individual sites showed that the subsoil represents an important pool of K_{ex}: from 356 kg K/ha (site C) up to 858 kg K/ha (site A). The potassium from the subsoil is well used by plants, which goes against the changes in the content of the available potassium depending

Table 6. The average contents of the different potassium forms in the 30–60 cm soil depth (mg K/kg)

Location	Extractant			
	K_{H2O}	K_{M3}	K_{ex}	K_{ne}
A	21[a]	232[a]	196[a]	1800[a]
C	14[b]	110[b]	78[b]	3003[b]
E	22[b]	147[c]	106[c]	846[c]

K_{H2O} – water; K_{M3} – Mehlich 3; K_{ex} – ammonium acetate; K_{ne} – the non-exchangeable potassium; the values followed by the same letter are not significantly different ($P < 0.05$) between the experimental sites

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Table 7. The K extraction ability of the different methods compared to K_{ar} (expressed in % of K_{ar})

Location	K_{H2O}	K_{M3}	K_{ex}	K_{ne}	K_{ar}
	(%)				(mg K/kg)
Topsoil (0–30 cm)					
A	0.25	2.37	2.84	14.8	9 249
C	0.31	1.96	2.06	36.7	7 652
E	0.33	1.66	2.07	12.2	7 715
Subsoil (30–60 cm)					
A	0.25	2.82	2.38	21.9	8 225
C	0.13	1.02	0.73	27.9	10 748
E	0.24	1.58	1.14	9.11	9 290

K_{H2O} – water; K_{M3} – Mehlich 3; K_{ex} – ammonium acetate; K_{ne} – the non-exchangeable potassium; K_{ar} – the aqua regia extraction

on the fertilisation intensity (Witter & Johansson 2001; Kautz et al. 2013; Mitchell & Huluk 2016). The ratio of the subsoil K to the total K uptake by the plants depends on the crop grown (the density and depth of the root system as well as the ability of the plants to take up the K), the soil properties (the soil type and class, the contents of K in the topsoil and subsoil, the CEC and its saturation with the other cations) and environmental factors (the sum of the precipitation and distribution during the vegetation period). Renger et al. (1993) reported an extreme interval of 9% up to 70%.

Less soluble potassium compounds are described as "potentially available" or "slowly available K", "reserve K", "mineral K" or "acid-extractable K". Liu & Bates (1990) reported that the content of K_{ne} provides good information on the amount of potentially available K.

In our observation, the content of K_{ne} was calculated according to Wood & DeTurk (1941). As shown in Table 4, the sites significantly differed in the K content. The highest contents were observed at site C (average 2 806 mg K/kg) as compared to the low average values obtained at site E, 965 mg K/kg.

Even higher contents than K_{ne} were measured for the residual K (K_{ar}); A – 9 249 mg K/kg; C – 7 652 mg K/kg; E – 7 715 mg K/kg. However, this does not apply to the total potassium content in the soil (K_{tot}). During our experiment, K_{tot} was not estimated, but these values would be several times higher than K_{ar}. As reported by Andrist-Rangel et al. (2006), the aqua regia extraction mobilised 5–45% of the total K content. Generally, the level of aqua regia extractability is higher from clay particles compared to the sand fraction. When using aqua regia as a strong extraction agent, the ratio of the non-exchangeable K (K_{ne}) was only 12.2–36.6% in the topsoil and 9.1–27.9% in the subsoil (Table 7). The ratio of K_{ex} was 0.73–2.84%; the lowest values were obtained at site C.

Calculation of K reserves in the topsoil. In our observation, the results of the analyses from 1996 were compared with the values obtained in 2017 (for each parcel, individually). The differences in the K_{ex} content (kg K/ha) are summarised in Table 8. There was a significant decreasing tendency of the potassium content during the experimental period, also by the K-fertilised sites. The largest decrease was obtained at site C, on average by 18.6 kg K/ha/year (average from treatment Cont. and mineral N). Simonsson et al. (2007) determined a decrease in the content of K_{ex} in the topsoil by 3–18 kg K/ha/year by the control K treatment. The authors also reported a decrease in some treatments, despite the stable K balance. Compared to their results, Khan et al. (2014) showed an increase in the K_{ex} even at a short-term negative balance. Madaras et al. (2010) derived the K-stabilising application rate K-SAR in relation to the soil properties and environmental factors. For the potato production region (typical of site C), the value was set at 222 kg K/ha/year (Madaras et al. 2010). In our experiment, the highest K dose was applied with FYM1 (143 kg K/ha/year)

Table 8. The changes between the K_{ex} contents in the topsoil (0–30 cm) after 21 years of the experiment duration (kg K/ha)

Location	Cont	SS1	FYM 1	FYM 1/2	N	NPK	N + St
A	-17^{a}	71^{ab}	90^{ab}	69^{ab}	-141^{a}	254^{b}	-34^{a}
C	-396^{a}	-427^{a}	-36^{c}	-194^{b}	-384^{a}	-119^{b}	-601^{a}
E	-337^{a}	-242^{a}	130^{c}	-23^{b}	-250^{a}	143^{c}	-106^{a}

Cont – control; SS1 – sewage sludge; FYM1 – farmyard manure; FYM1/2 – half dose of farmyard manure + N in mineral nitrogen fertiliser; NPK – mineral fertiliser; N + St – spring barley straw + N in mineral nitrogen fertiliser; $\Delta K_{ex} = K_{ex/1996} - K_{ex/2017}$; the values followed by the same letter are not significantly different ($P < 0.05$) between the experimental plots

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and with NPK (90 kg K/ha/year). It is, thus, evident that the potassium applied in our experiment was lower than the K-SAR levels determined by Madaras et al. (2010).

The amount of potassium released from the K_{ne} forms was calculated using the values given in Table 8 and the balance presented in Table 3. The calculation used the average values of the treatments with no potassium (control and mineral N). This method was chosen to extend the evaluated datasets. Another precondition is the fact that the K_{ex} values in the subsoil did not change which is in accordance with our experiment. The following values were calculated according to Blake et al. (1999):

average crop uptake (kg K/ha/year) – **Δ** content K_{ex} (kg K/ha/year) = K released from K_{ne} (kg K/ha/year)

This basic equation can be presented in detailed form for our experiments as follows:

$$K_{rel} = \left[\left(\frac{\text{con} + \text{N}}{2}\right) : y_{exp}\right] - \left[\left(\frac{\Delta K_{excon} + \Delta K_{exN}}{2}\right) : y_{exp}\right]$$

where:

K_{rel} – the K_{ex} released from K_{ne} by the treatments without K fertilising (in kg K/ha/year)

con + N – the sum of the average crop uptake by the control and mineral N treatment (without K fertilising) for the whole experiment duration (in kg/ha)

$\Delta K_{excon} + \Delta K_{exN}$ – the sum of the ΔK_{ex} content in the soil by the control and N treatments (in kg K/ha)

y_{exp} – the experiment duration in years

Based on the detailed equation, the calculation of K_{rel} (in kg K/ha/year) according to the experimental sites was the following:

$$\text{Site A: } \left[\left(\frac{1\,467 + 1\,599}{2}\right) : 21\right] - \left[\left(\frac{17 + 141}{2}\right) : 21\right] = 69.3$$

$$\text{Site C: } \left[\left(\frac{1\,092 + 1\,921}{2}\right) : 21\right] - \left[\left(\frac{392 + 384}{2}\right) : 21\right] = 53.1$$

$$\text{Site E: } \left[\left(\frac{1\,001 + 1\,536}{2}\right) : 21\right] - \left[\left(\frac{337 + 250}{2}\right) : 21\right] = 46.4$$

Our results are in good agreement with the findings of Simonsson et al. (2007) and Holmqvist et al. (2003). Based on the condition that about 50% of the K_{ne} reserves in the topsoil may be taken up by the plants and that the K_{ne} pool is not increased by less mobile reserves, the following time horizon for the individual sites was determined:

Site A:

average K_{ne} content: 1 370 mg/kg ≈ 5 754 kg K/ha (50% taken up by plants) ≈ 2 877 kg K/ha;

2 877 kg K/ha: 69.3 kg K/ha/year (released from the K_{ne}) = 41.5 years.

Site B:

average K_{ne} content: 2 808 mg/kg ≈ 10 952 kg K/ha (50% taken up by plants) ≈ 5 476 kg K/ha;

5 476 kg K/ha: 53.1 kg K/ha/year (released from the K_{ne}) = 103.9 years.

Site E:

average K_{ne} content: 942 mg/kg ≈ 4 240 kg K/ha (50% taken up by plants) ≈ 2 120 kg K/ha;

2 120 kg K/ha: 46.4 kg K/ha/year (released from the K_{ne}) = 45.7 years.

This is, however, a simplified calculation, and in compliance with the results of Kitagawa et al. (2018), it stresses the importance to determine the K_{ne} for the prediction and calculation of the optimal potassium dosage, especially in the case of risk management.

CONLUSION

Long-term stationary field experiments with different fertilisation systems were carried out to study the balance of potassium and the changes in its content in the topsoil and subsoil. Positive correlations between the contents of the available K in the topsoil and the potassium balance (K inputs – K outputs) were observed. Depending on the soil properties, the ratio of the non-exchangeable K (K_{ne}) was 12–37% of the values obtained due to the aqua regia extraction. Experiments were used to determine the potassium release from the K_{ne} forms that is involved in plant nutrition, which replenishes the pool of available K. Depending on the site, this amount was 46–69 kg K/ha/year.

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