Potassium leaching following silage maize on a productive sandy soil

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ABSTRACT

Relatively little is known about potassium leaching losses following harvest of silage maize. While direct negative impacts on the environment are unlikely, losses of K with leaching need to be known for accurate balancing, especially on coarse textured soils, where K can be a critical element. In a four-year field experiment the effects of fertilizer forms (inorganic, cattle slurry and pig slurry) and four levels of N input (0, 80, 160, 240 kg N/ha) with corresponding amounts of K on the nutrient balances and leaching of K from silage maize grown on a sandy soil were investigated using suction cups. After four years, surplus of K from cattle slurry led to higher lactate-soluble K in the topsoil. Potassium leaching differed between years with different amounts of rainfall during winter. Annual leaching losses of K increased with N and K input and amounted to 38 kg K/ha, while fertilizer form had no significant effect. Losses of K increased with increasing N leaching (R^2 = 0.69). We conclude that in maize production on coarse textured soils and under conditions of high N leaching (86–152 kg N/ha), K leaching can be large (6–84 kg K/ha) and constitutes a relevant part of K balances (–84 to +127 kg K/ha).

Keywords: cation translocation; K balances; K management; N leaching; *Zea mays*

Potassium (K) as a major nutrient element is of agronomic interest, particularly for forage farming (Kayser and Isselstein 2005). Forage crops, grass and lucerne, but maize as well, need and take up K in great amounts. Direct adverse effects of K emitted to the environment are not known (Askegaard et al. 2004). Sandy soils and organic soils are generally poor in K-bearing minerals and in non-exchangeable K; they release little K by weathering and have low adsorption capacities (Mengel and Kirkby 1987). The cycling and availability of K in these soils is therefore quite dynamic and easily affected by management practices (Askegaard and Eriksen 2000, Askegaard et al. 2003). The way in which crops respond to K and the amount needed depends to a considerable extent on the level of nitrogen nutrition (Wilkinson et al. 2000, Alfaro et al. 2003, Fortune et al. 2005). Potassium leaching is generally dependent on the amount of exchangeable K in the soil, which to a great extent reflects the level of K input and resulting K surpluses (Askegaard et al. 2003, Alfaro et al. 2004, Kayser et al. 2007). On the farm and field level surpluses from intensive animal production and fertilizer input, or negative balances for K, which might occur in organic forage farming, rapidly affect the concentrations of exchangeable K in the topsoil (Öborn et al. 2005). Cropping systems with continuously large negative balances are not sustainable in the long-term and large losses of K are wasting of a limited resource (Askegaard et al. 2004). Information on K leaching from maize on sandy soils in northwest Europe is scarce. In a four-year field experiment we tested the hypotheses that (i) different fertilizer types (pig slurry, cattle slurry, mineral N) and increasing N levels, coupled with different K inputs, have an effect on K and N leaching, (ii) K leaching can be explained by maize yields and nutrient balances on a productive sandy soil and that (iii) the extent of K leaching can be controlled by nutrient input.

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MATERIAL AND METHODS

Site. The experimental site was located near Friesoythe in northwest Germany (52°56'44''N, 7°50'17''E). The original soil type can be described as a Gleyic Podzol (WRB) (~Typic Haplaquod, Soil Taxonomy) covered with a relatively shallow layer (0–50 cm) of degraded peat (high moor) which had been converted into an Anthric Podzol (WRB) by deep-ploughing in 1975. From that time onwards it was used as arable land with moderate to high inputs of manure (120–160 kg N/ha). The soil profile consists of a recent plough layer (0–30 cm), a deep-ploughed subsoil layer (30–80 cm), and an undisturbed sand layer below 80 cm. The groundwater level is at the depth 95–140 cm in winter. The texture in the topsoil is sand to loamy sand with 87% sand (50% fine sand), 11% silt and 2% clay on average. Field capacity in the effective rooting depth (< 80 cm) was about 140 mm. Deep-ploughed soils are characterized by 6–8% of organic matter, here 6.8%, relatively good natural drainage and good storage capacities for nutrients and water due to the organic part, but also a moderate to high risk of leaching (Scheffer and Schachtschabel 2002). During the course of the experiment all treatments had sufficient to high amounts of plant available macro nutrients in the topsoil (n = 20, 0–30 cm: P, 148 mg/kg; K, 83 mg/kg; pH, 4.8; total C, 4.04; total N, 0.19; C:N ratio, 21:1).

Set-up of the experiment. The experiment had a two-factorial split-plot design investigating as main factors the form of N input (mineral, cattle and pig slurry; whole-plots) and the amount of N input (0, 80, 160, and 240 kg N/ha; sub-plots) and was conducted over a period of 4 years from 1994 to 1998. In slurries increasing N inputs were coupled with larger amounts of K applied to the maize, for the treatments with mineral N (CAN – calcium-ammonium nitrate) and no N, K (and P) was provided in mineral form. Nitrogen input was based on total N. Treatments were repeated four times and sub-plot size was 72 m^2; plots and treatments were fixed over all years. Maize (*Zea mays* L. cv. Magda) was cultivated in monoculture and was planted within ± 5 days of May 1 and harvested within ± 5 days of October 1; high animal density and biogas production monoculture of maize is quite common in the region. The main target variables were dry matter yield (DM), N and K offtake with harvest and nitrate and K leaching. Three suction cups per plot were installed at 70 cm depth to measure N and K concentrations in leaching water during winter (October–April). Each cup was sampled every 1 or 2 weeks during the leaching period from approximately mid-October to April. Each sample was analysed for nitrate, K was determined every 4 weeks.

The K and NO_3-N leaching losses were calculated as the product of the nutrient concentration and the amount of water percolating through the profile during a given time. It was assumed that after the soil water content had reached field capacity in autumn, daily drainage equalled rainfall minus evapotranspiration (DVWK 1996). The data for leaching to start was inferred from soil and meteorological data. Summing the nitrate and K leaching for all sample dates while percolation occurred gave a total loss over winter.

The N fertilization was divided into two applications, with 70% applied after ploughing in April and 30% given at a later date before the closing of plant rows in June. The need for P was met by the application of a band of mineral fertilizer placed 5 cm below and 5 cm to the side of the maize seed with 30 kg P/ha as triple phosphate to all treatments. Weeds were controlled by herbicides.

Table 1 shows the climatic conditions for the experimental years. For the experimental site meteorological data from a station of the German Weather Service (Friesoythe-Edewechterdamm) about 10 km away were obtained. Apart from the second winter, which was exceptionally cool and dry, winter seasons of the other years were relatively mild with average to high rainfall. The summer of year three differed from the other years as it was quite cold and precipitation was below average apart from August and also October, which had incidents of high rainfall.

Chemical and statistical analyses and calculations. The pH in soil samples was determined in a 0.01 mol/L $CaCl_2$ solution. Total carbon (TC) was determined by means of an infrared-cell in a LECO SC 444 analyzer (Leco Ltd., Hazel Grove, UK). All total nitrogen contents (TN) in soil and plant material were determined through an automated N analyser (Heraeus, Hanau, Germany). Plant available potassium (K_{ex}) and phosphorus were extracted from soil samples following the DL-method (double lactate) as described by Hoffmann (1991). Filtered extracts from soil and plant and water samples were analysed for K with an atomic-absorption-spectrometer (Varian SpectrAA300, Darmstadt, Germany); nitrate concentrations were determined photometrically with an EPOS 5060 auto-analyzer (Eppendorf, Hamburg, Germany).

Statistical data analysis was carried out using the Genstat 6.1 software package (VSNi Ltd.,

Table 1. Mean daily temperature, annual rainfall, and climatic water balance for 4 years

Year (May–April)	Mean daily temperature (°C)	Annual rainfall (mm)	Climatic water balance (mm)
1	10.0	959.0	430.1
2	8.5	542.3	55.2
3	8.7	715.6	201.9
4	10.4	704.5	98.7
Long-term average	8.7	783.1	293.1

Hemel Hempstead, UK). Analysis of variance (ANOVA) considered two factors in a split-plot design with four replications. Each block (replicate) was divided into three whole-plots for the three fertilizer forms (F) and the different levels of N (amount of fertilizer, A) were randomly allocated in sub-plots within each whole plot. We checked the assumptions of the statistical models using residual plots. To consider the effect of 4 consecutive experimental years, we applied the

Table 2. Nutrient input per year with mineral fertilizers (CAN, KCl), cattle slurry (CS) and pig slurry (PS). Results from ANOVA (repeated measurements; *P*-values) for dry matter (DM) yield, K surplus (K input – K offtake), and K leaching; means as averaged over 4 experimental years

	N input	K input	DM yield (t/ha)	K surplus	K leaching
	(kg/ha)			(kg/ha)	
Fertilizer form (F)			0.843	< 0.001	0.064
Amount of N fertilizer (A)			< 0.001	< 0.001	< 0.001
Year (Y)			< 0.001	< 0.001	< 0.001
F × A			0.393	< 0.001	0.282
Y × F			0.475	0.011	0.031
Y × A			0.266	0.051	0.012
Y × F × A			0.944	0.985	0.899
CAN	0	200[1]	13.65	72	34
	80	200[1]	14.37	53	40
	160	200[1]	15.20	37	39
	240	200[1]	15.56	27	53
CS	0	200[1]	13.63	81	28
	80	93	14.32	–61	39
	160	187	14.26	37	43
	240	280	14.81	127	43
PS	0	200[1]	13.50	77	24
	80	46	13.80	–84	32
	160	91	15.13	–63	35
	240	137	15.08	–15	45
LSD F × A			1.938 (0.902)[2]	23.5 (14.7)[2]	9.2 (8.7)[2]
LSD F			1.885	21.7	6.4
LSD A			0.521	8.5	5.0

[1]in mineral form as KCl, muriate of potash (40); CAN – calcium-ammonium-nitrate; CS: 57 g/kg DM; 3.0 N, 0.6 P, and 3.5 K (kg/m^3); PS: 63 g/kg DM; 6.3 N, 1.8 P, and 3.6 K (kg/m^3); [2]when comparing within the same level of fertilizer form; *LSD* – least significant difference (*P* = 0.05)

procedure 'Arepmeasure' in Genstat which deals with repeated measurements.

RESULTS AND DISCUSSION

In the slurry treatments N and K input were not fully synchronized which consequently led to K imbalances (Table 2): K surpluses for treatments with N fertilization were positive for CAN (37 kg K/ha), increasing from –61 to +127 kg K/ha for cattle slurry and negative (–15 to –84 kg K/ha) for pig slurry. Leaching losses of K with silage maize averaged at 40 kg/ha (6–84 kg K/ha). These K losses appear to be large when compared to the loss of 6 kg K/ha in an adjacent cut grassland experiment with K surpluses of 50 kg/ha or losses of 25 kg K/ha with surpluses of 155 kg K/ha. Nitrate leaching losses of cut grassland were typically small with 5–14 kg N/ha for inputs of 0–320 kg N/ha (Askegaard and Eriksen 2000, Alfaro et al. 2003, Kayser et al. 2007), while leaching of NO_3-N under silage maize production in our experiments was as high as 86 kg N/ha when no fertilizer N was applied and amounted to 152 kg/ha with 240 kg N/ha from mineral or organic sources. The deep-ploughed organic-sandy soil must have mineralized large amounts of N under regular tillage to provide ample N even with small N input from fertilizer (Kayser et al. 2011). In grassland, losses of K could be related to actual K input, surpluses and the level of exchangeable K, which depends, especially in coarse textured soils, on the surplus of K. The situation was less straightforward in the maize field. Here, K_{ex} was related to K surpluses (Figure 1a), but K leaching seemed to follow the pattern of NO_3-N leaching as well (Figure 1b, Table 2). The interrelated processes determining the extent of K losses might be described in two steps: (1) As K concentrations in biomass offtake (on average 1.02%) hardly differed between years and did not increase with increasing K input, the decisive factor for K off-take was the N input. Exchangeable K in topsoil was then higher with increasing surpluses and in turn led to increased leaching losses of K (Table 2, Figure 1a). (2) Due to the different levels of K_{ex} in soil and actual fertilizer K input, the K losses during winter were then mainly a consequence of the amount of water leached (rainfall during winter) and the extent of NO_3-N leaching in different years (Figure 1b, Kayser and Isselstein 2005).

The processes that drive K translocation and subsequent leaching are different from those of N. The movement of exchangeable cations depends upon the concentration of free anions, as cations do not move independently. When anions such as nitrate and chloride are leached, equivalent amounts of cations will also be translocated as counterions (Tinker and Nye 2000, Öborn et al. 2005).

Leaching losses of K differed with years and increased with N and K input, while the differences between fertilizer forms, that is mineral or cattle and pig slurry, were small (Figure 2). Whether K was applied in mineral form or with slurries was not relevant, as the fertilizer replacement value of K in slurries is regarded as 100%. In contrast to other major nutrients K, is almost totally water soluble as K^+ and is thus readily available (Mengel and Kirkby 1987). Potassium balances and K leach-

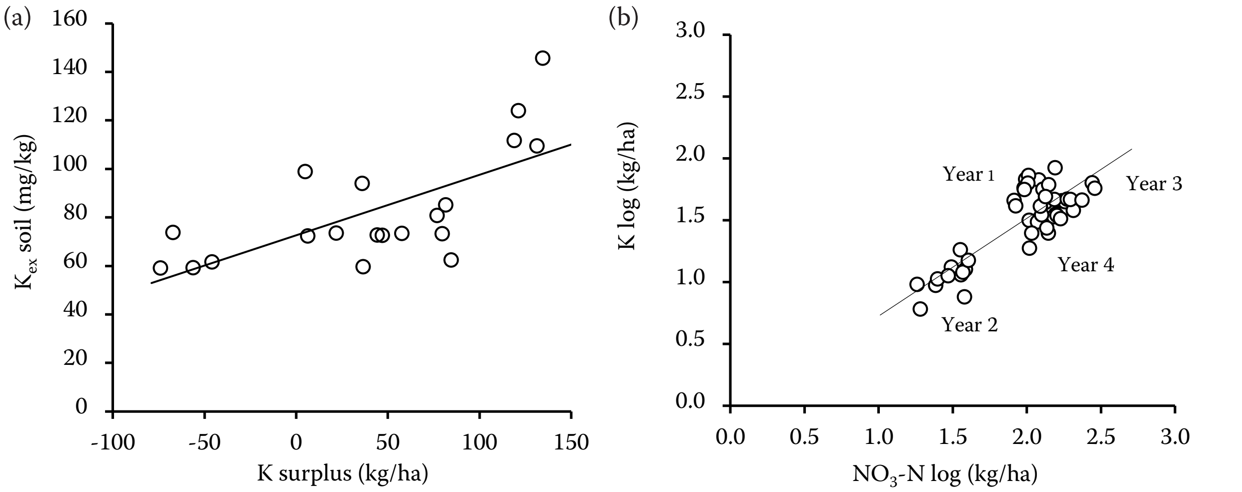

Figure 1. (a) Relationship between K surplus and lactate extractable K (K_{ex}) in the topsoil for cattle slurry treatment after 4 years; $y = 0.2496x + 72.63$; adj. $R^2 = 0.44$; s.e. = 17.8; $P < 0.001$; (b) Relationship between NO_3-N leaching (kg/ha) and K leaching (kg/ha) based on years and treatments transformed by logarithm: $y = 0.7909x - 0.066$; adj. $R^2 = 0.69$; s.e. = 0.0773; $P < 0.001$

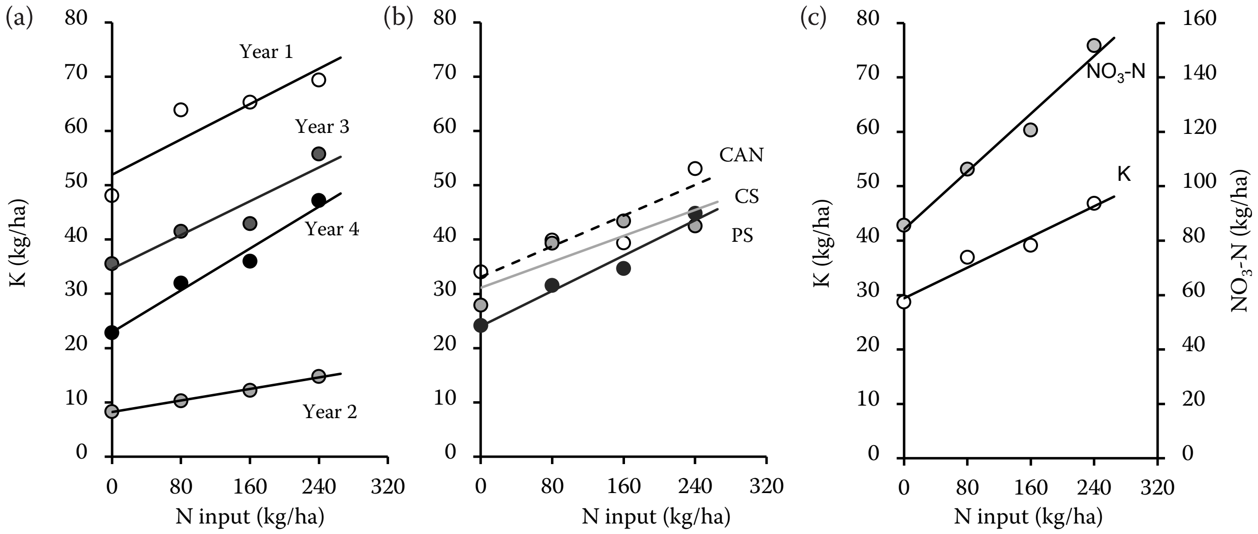

Figure 2. K leaching losses during winter depending on level of N input, 0–240 kg N/ha and corresponding K input (Table 2); (a) experimental years averaged over fertilizer forms; (b) fertilizer forms averaged over four years; (c) K and NO_3-N leaching losses averaged over all years and fertilizer forms (CAN – mineral N; CS – cattle slurry; PS – pig slurry)

ing were closely related to N input and N leaching losses (Figures 1, 2). In an analysis of the effect of N fertilizer form and N input on yields, N balances, soil mineral N (SMN) and nitrate leaching, Kayser et al. (2011) found no significant differences between pig and cattle slurries and mineral fertilizer. The supply of N from soil resources was very high and had a pronounced effect on the efficiency of fertilizer and manure N. Thus, increasing amounts of N led to a significantly linear increase in yields, SMN and N leaching, but at an already high level for the control N0.

Potassium balances require the accurate determination of K leaching losses (Askegaard et al. 2004). The large K losses of up to 80 kg K/ha in our experiment constitute a significant amount of K, which in some situations needs to be balanced by soil reserves or by K fertilization. However, K supply from soil reserves is limited and return of K in organic agriculture might not always be sufficient (Askegaard et al. 2003). Under circumstances of large N supply and N leaching, it is likely that with equally large K offtake, negative K balances and K leaching, the level of exchangeable K will decrease. Under conditions of intensive animal production and frequent application of slurry, resulting in constant K surpluses, K levels might further increase with the consequence of even larger K losses. Agronomic management needs to react in order to avoid K deficiency or the unnecessary waste of a limited resource. For maize production on organic sandy soils, this requires balanced nutrient inputs – including manures, consideration of the mineralization potential of the soil and management practices such as the use of understorey or catch crops (Wachendorf et al. 2006, Kayser et al. 2011).

Further research is needed to elucidate these complex processes and to look into interactions of K with N from different sources, especially on coarse textured soils which respond quickly to surpluses or deficiencies.

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