Potassium Release in Representative Maize-Producing Soils of Thailand

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Ammonium acetate K does not adequately measure available K in the mineralogically diverse maize (*Zea mays* L.)-producing soils of Thailand. The objective of this study was to understand the causes of this problem and propose a solution using laboratory and greenhouse experiments to examine the release patterns and the availability of exchangeable and nonexchangeable K. Eight kaolinitic and smectitic soils were examined for the release of K in each soil fraction (sand, silt, and clay) using the Ca-resin successive extraction method. The data were fitted using parabolic diffusion, power function, and segmented straight line regression models. The power function and the segmented regression model fitted the data well. All soils were exhaustively cropped with maize in the greenhouse until the soils became K deficient. The results indicated that a segmented regression model described nonexchangeable K release to the Ca resin and to plants in a way that seemed to correspond with earlier predictions. According to the model, there were two fractions of nonexchangeable K, which were released at distinctly different rates. The greenhouse study yielded fast and slow K release rates from the nonexchangeable K pool of 0.45 to 0.85 and 0 mg kg^{-1} d^{-1}, respectively, in kaolinitic soils and 1.60 to 1.98 and 0.27 to 0.52 mg kg^{-1} d^{-1}, respectively, in smectitic soils. Our results suggested that NH$_4$OAc-extractable K was suitable and sufficient to determine plant-available K in kaolinitic soils. In contrast, a successive Ca-resin extraction characterization plus NH$_4$OAc-extractable K was required to determine plant-available K in smectitic soils.

Abbreviations: Cd, Chai Badan; CEC, cation exchange capacity; K$_{nonex}$, nonexchangeable K; Lb, Lob Buri; Ln, Lam Narai; Pc, Pak Chong; Ps, Phu Sana; RMS, residual mean square; Suk, Satuk; Tk, Takhli; Wn, Warin.

Maize is an important economic field crop widely produced in the north, northeast, and central parts of Thailand. The clay mineralogy of soils in these areas is dominated by smectite and kaolinite, and in some soils a small amount of illite is also found (Soil Survey Staff, 1999). While a response of maize to K fertilizer was found in soils dominated by kaolinite, no response was found in soils dominated by smectite (Attanandana et al., 2004; Attanandana and Teeraphorn, 2005). It is believed that K is sufficient for plant growth in the smectitic soils but insufficient in kaolinitic soils. The soil test method used to establish K fertilizer recommendations in Thailand (Land Development Department, 2006) is the 1 mol L^{-1} NH$_4$OAc method, which only extracts solution and exchangeable K (Cox et al., 1999). McLean and Watson (1985) indicated that when the exchangeable K approached the critical level, the availability of K to plants tended to be regulated by the release of nonexchangeable K. Wang et al. (2004) indicated that nonexchangeable K probably controlled the overall buffering capacity of a low-exchangeable-K soil. The inadequacy of NH$_4$OAc to determine plant-available K was found mostly in 2:1 clay soils, for example, illitic (Eckert and Watson, 1996), vermiculitic (Cassman et al., 1990), and smectitic (Schindler et al., 2002) soils. Nonexchangeable K is held between adjacent tetrahedral layers of weathered dioctahedral and trioctahedral micas (Mengel et al., 1998) and released to plants by diffusion-controlled processes (Srinivasarao et al., 2006; Jalali, 2005). The amount of nonexchangeable K has been estimated by various extractants and methods, such as boiling HNO$_3$ (Loganathan et al., 1995), oxalic and citric acid extraction (Song and Huang, 1988), electro-ultrafiltration (Mengel et al., 1998), sodium tetraphenylboron extraction (Cox et al., 1999), successive extractions with cation exchange resins (Rahmatullah and Mengel, 2000), and exhaustive plant extraction of K (Cox et al., 1996; Havlin and Westfall, 1985). The release of K to plants was mostly influenced by the amounts and mineralogy of the clay and silt fractions (Jalali, 2005; Srinivasarao et al., 2006). The major advantage of using a cation exchange resin

to extract K is that, like plant roots, it acts as a sink for the released K (Helmke and Sparks, 1996; Askegaard et al., 2005).

The pattern of K release is usually described by a linear regression of the first-order kinetics, parabolic diffusion, power function, or the Elovich equations. The regression equations have a straight line with a slope, b, indicating a steady release rate of K in the soils. In contrast, other research showed that the release of K, studied by various successive extraction methods, was characterized by a rapid, initial release rate followed by a subsequent slower rate of release (Mengel et al., 1998; Benipal et al. (2005). These results suggested that the release of K from the soil is probably a complex reaction, possibly resulting from two distinct processes. A segmented regression model has been proposed to describe the complex reactions with different mechanisms found in soil and plant nutrition studies (Anderson and Nelson, 1975; Shuai et al., 2003). The straight lines with different slopes (b) and join points (a) of the segmented regression model describe the different rate processes as different mechanisms (Cox and Barnes, 2002; Shuai et al., 2003).

A hypothesis of this study was that the amount of nonexchangeable K released into the soil solution and available to plants is controlled by the rate of K release, which depends on the amount and type of clay minerals in each soil. The objectives of this study were to determine (i) the kinetics of the K release pattern in representative maize-growing soils, and (ii) the amount and rate of nonexchangeable K release to plants so that plant K sufficiency can be more accurately predicted.

MATERIALS AND METHODS
The Experimental Soils

Samples from the 0- to 20-cm depth of eight typical maize soils were collected from farm fields in the Central Plain and northeast regions of Thailand. These were Phu Sana, Satuk, Warin, Pak Chong, Lop Buri, Chai Badan, Takhli, and Lam Narai soils. The taxonomy and chemical and physical properties are presented in Table 1. Soil pH was determined in a 1:1 soil/water paste. Exchangeable K was extracted by 1 mol L^{-1} NH_4OAc. Nonexchangeable K was determined by the boiling HNO_3 method and total K by HF digestion (Helmke and Sparks, 1996). Cation exchange capacity (CEC) was measured by the saturation method (Summer and Miller, 1996). Particle size analysis was determined by the pipette method (Gee and

Bauder, 1986). A mineralogical analysis of the clay fraction was performed using the procedure given by Kunze and Dixon (1986) and x-ray diffraction.

Soil Potassium Release to Calcium Resin

Soil fractions were prepared by removing $CaCO_3$ with dilute HCl and organic matter with H_2O_2 (Kunze and Dixon, 1986). Iron oxides were removed by the Na dithionite–citrate–bicarbonate method. The concentration of Na in the dithionite and citrate solutions was 0.4 and 0.1 mol L^{-1}, respectively. The sand fraction was separated by wet sieving, and the silt and clay fractions by the pipette method (Gee and Bauder, 1986). Potassium release from the soil fractions was determined by successive extraction with a Ca-saturated cation exchange resin (200 $cmol_c$ kg^{-1}, >0.85 mm). The Ca-saturated resin was prepared by slowly leaching Na resin with 1 mol L^{-1} $CaCl_2$ at pH 7.0 (Havlin et al., 1985). Two grams of air-dry soil fraction from each sample was placed in a 120-mL bottle with 1.0 mL of deionized water and allowed to reach equilibrium overnight. Four grams of moist Ca resin and 10 mL of deionized water were then added to each soil sample. The soil–resin–water mixture was equilibrated at 25°C for 0 to 600 h (0, 60, 120, 240, 360, 480, and 600 h). At the end of each reaction period, the resin was separated from the soil on a 0.50-mm sieve with 25 mL of deionized water. The soil suspension was centrifuged (12,000 rpm) for 10 min. The supernatant solution was analyzed for K by atomic absorption spectrophotometry. The separated resin was leached with 150 mL of 0.01 mol L^{-1} $CaCl_2$ and the leachate was analyzed for K by atomic absorption spectrophotometry. A fresh batch of Ca resin was added to the reaction flask and soil, and incubated for the subsequent reaction period. The cumulative K release in a given time period was calculated as the sum of the K adsorbed on the resin and the K in the supernatant solution. Blank samples were treated the same as the soil samples. The total cumulative K of each soil was the summation of the K released based on the weight contribution of the sand, silt, and clay fractions from each soil (Havlin et al., 1985).

Potassium Exhaustion Pot Experiment

A pot experiment was performed with the eight soils using a randomized complete block experimental design that consisted of a no-K fertilizer treatment and a 200 mg K kg^{-1} treatment in four replications. Soils were air dried and ground to pass a 6-mm sieve, and

Table 1. Soil taxonomy, selected chemical and physical properties, and mineralogy of the eight soils studied.

Soil series	Subgroup†	pH	Silt	Clay	CEC‡	NH_4OAc-K	HNO_3–K	HF-K	Mineralogy§
			— g kg^{-1} —-		$cmol_c$ kg^{-1}	——— mg K kg soil^{-1} ———-—			
Kaolinitic soils									
Phu Sana	Kanhaplic Haplustult	4.5	255	262	5.9	39	52	1899	Ka, Ve, Il, Qu
Satuk	Typic Paleustult	4.6	49	232	3.1	34	57	862	Ka, Il, Qu
Warin	Typic Kandiustult	4.6	42	247	2.4	18	63	1273	Ka, Il, Qu
Pak Chong	Rhodic Kandiustox	5.3	331	464	11.0	107	126	2146	Ka, Sm, Il, Qu
Smectitic soils									
Lop Buri	Typic Haplustert	6.6	132	802	53.5	139	170	6577	Sm, Ve
Chai Badan	Leptic Haplustert	7.3	129	759	57.2	375	431	5036	Sm, Il, Ka, Qu
Takhli	Entic Haplustoll	7.7	510	380	29.2	85	123	1629	Sm
Lam Narai	Vertic Haplustoll	7.5	111	802	46.9	60	102	1041	Sm, Ka

† Soil Survey Staff (1999).

‡ Cation exchange capacity.

§ Ka, kaolinite; Ve, vermiculite; Il, illite; Qu, quartz; Sm, smectite.

10 kg of each soil was weighed into each pot. Ten maize seeds were placed about 2 cm below the soil surface and 5 d after emergence each pot was thinned to two seedlings. Nitrogen, at 100 mg N kg^{-1} as NH_4NO_3, and 56 mg P kg^{-1} as $CaH_2PO_4 \cdot 2H_2O$ were applied to the soil at 10 d after emergence. All fertilizers were added in liquid form to facilitate distribution. The aboveground part of the maize plant was cut at the soil surface at the tasseling stage (55 d after emergence) because >90% of the total K uptake is usually accumulated by that stage (Ritchie et al., 1997). The maize tissue was dried at 70°C for 48 h, crushed, and ground to pass a 0.5-mm sieve. A 0.5-g subsample was digested by a HNO_3–$HClO_4$ mixture at 180 to 200°C (Jones, 2001) and the K concentration determined. The roots of the maize plant were crushed and remixed with the soil. Soil samples were taken before and after cropping for NH_4OAc-extractable K determination (Helmke and Sparks, 1996). Up to four maize crops were grown successively in each pot. The data of the K exhaustion experiment were used to quantify the release of nonexchangeable K from the soil to maize. The quantity of nonexchangeable K released to the maize was calculated by the following K balance equation (Havlin and Westfall, 1985):

$$K_{nonex} = K_{removed} - \left(K_{ex\ before} - K_{ex\ after} \right) \qquad [1]$$

where K_{nonex} is the quantity of K released from the nonexchangeable pool to the plant (mg kg^{-1}), $K_{removed}$ is the cumulative K uptake by maize (mg kg^{-1}), and $K_{ex\ before}$ and $K_{ex\ after}$ are the NH_4OAc-extractable K before and after each maize crop (mg kg^{-1}).

Data Analysis

The K release to the Ca-saturated exchange resin and the cumulative K release resulting from the exhaustion cropping by maize were described by a linear form of the parabolic diffusion equation, a linear form of the power function equation, and a nonlinear segmented straight line equation:

Parabolic diffusion equation:

$$y = a + bt^{1/2} \qquad (t \geq 0) \qquad [2]$$

Power function equation:

$$\ln(y) = b \ln(t) \qquad [3]$$

Segmented straight line equation:

$$y = b_1 \min(node, x) + b_2 \max(node, x) - c \qquad [4]$$

where y is the cumulative K release (mg kg^{-1}), t is time, a and b are estimated parameter values, b_1 is the slope of the first segment, node is the x value corresponding to the join point between the two straight lines, b_2 is the slope of the second segment, and c is the y intercept of the segmented straight line equation.

Equation [4] is a more general form of the linear response plateau equation sometimes used to fit response and plateau responses of the type described by Anderson and Nelson (1975):

$$y = b_0 + b_1 \min(time, node) \qquad [5]$$

where b_0 is the y intercept and b_1 is the slope of the response below the join point (node) of the plateau.

All equations were rewritten or modified to reflect the conditions of this study as follows. The parabolic diffusion equation was modified to reflect the initial condition as zero in the K-release process, i.e., there was no K on the Ca resin nor was there K uptake by the plants at time 0. This resulted in rewriting Eq. [2] as

$$y = bt^{1/2} \qquad (t \geq 0) \qquad [6]$$

The power equation is sometimes written as

$$\ln(y) = b \ln(t) \qquad [7]$$

We chose to rewrite it and fit it as

$$y = at^b \qquad [8]$$

so that the residuals would not need the back-transformation that would otherwise be required to compare the residual mean square fits of Eq. [7] with the other untransformed equations.

To also reflect the constraint that the equation should pass through the origin, the segmented straight line equation was modified and fitted as

$$y = b_1 \min(node, x) + b_2 \max(node, x) - b_2 node \qquad [9]$$

The revised models Eq. [6], [8], and [9] were fitted with the same statistical routine (SAS routine PROC NLIN, SAS Institute, 1985). This was necessary since the method of estimating the parameters and calculating the residual mean squares and parameters may differ for routines designed for models that are linear rather than nonlinear in their parameters. The parabolic diffusion model Eq. [6] and the power function model Eq. [8] remain linear in the parameters but were, nonetheless, fitted using the SAS routine for consistency. The residual mean square (RMS) resulting from fitting the equations thus could be used as one of several criteria to evaluate the fit of the equations for describing the release of K.

The coefficients of the fitted models can be used to interpret the release rates of nonexchangeable K. In the case of the segmented straight line model, the coefficients b_1 and b_2 quantify the slopes of the initial and subsequent straight lines, representing fast and slow rates of release, respectively, of K to the Ca resin and to plants.

RESULTS AND DISCUSSION

The discussion of this study can be simplified by grouping the soils based on the mineralogy of the clay (<2-mm) fraction (Table 1).

Kaolinitic soils: This group consisted of Phu Sana (Ps), Satuk (Suk), Warin (Wn), and Pak Chong (Pc) soils. The dominant clay mineral of these soils was kaolinite, with small amounts of vermiculite, illite, and quartz. A small amount of smectite was found in the Pc soil. Clay content and CEC ranged from 232 to 464 g kg^{-1} and 2.4 to 11.0 cmol$_c$ kg^{-1}, respectively (Table 1).

Smectitic soils: This group consisted of Lop Buri (Lb), Chai Badan (Cd), Takhli (Tk), and Lam Narai (Ln) soils. Smectite was the dominant clay mineral of these soils. A small amount of vermiculite was found in the Lb soil. The Cd soil contained a small amount of illite, kaolinite, and quartz. Clay content and CEC ranged from 380 to 802 g kg^{-1} and 29.2 to 57.2 cmol$_c$ kg^{-1}, respectively (Table 1).

Release of Potassium in Soil Fractions to Calcium Resin

The cumulative release of nonexchangeable K from the clay-size fraction between 0 and 600 h was greater than from the silt and sand fractions in all the soils. Ninety-six percent of the total K release was from the clay fraction and approximately 4% was from the sand and silt fractions. Benipal et al.
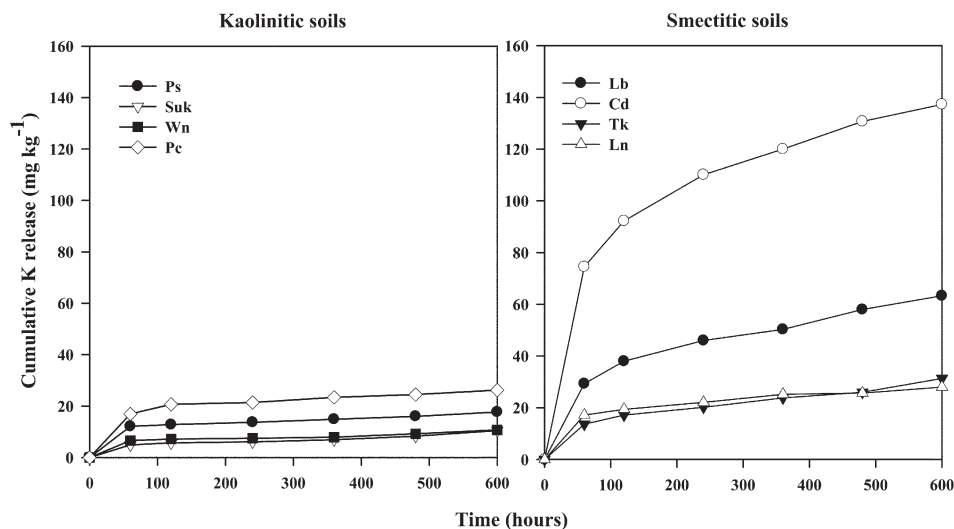
Fig. 1. Cumulative K release from soil fractions (sum of clay, silt, and sand fractions) of the eight soils to Ca resin from 0 to 600 h (~25 d). Soils: Ps, Phu Sana; Suk, Satuk; Wn, Warin; Pc, Pak Chong; Lb, Lop Buri; Cd, Chai Badan; Tk, Takhli; Ln, Lam Narai.

(2005) and Havlin and Westfall (1985) also showed that the cumulative K release from the clay fraction was larger than from the silt and sand fractions. The results indicated that about 50% of the cumulative nonexchangeable K released by all soils was released by the end of the initial reaction period (0–60 h) (Fig. 1), which was consistent with the findings of Askegaard et al. (2005). The total cumulative K release (sum of sand, silt, and clay fractions) from the kaolinitic soils was lower than that from the smectitic soils (Fig. 1), ranging from 11 to 27 mg kg^{-1} in kaolinitic soils and 29 to 137 mg kg^{-1} in smectitic soils. The amount of cumulative K release in Pc and Cd soils was higher than from other soils in their respective groups. This was probably the result of the large nonexchangeable K pools as indicated by the content of K extractable by boiling HNO_3 in these soils (Table 1). A close relationship was found between cumulative K release to Ca resin in all soils and the amount of K extracted by NH_4OAc ($r = 0.985$, $P = 0.01$) and boiling HNO_3 ($r = 0.987$, $P = 0.01$) from the initial samples. Because the soils prepared for the Ca-resin extraction are expected to be Na saturated given the high concentrations of Na from the dithionite and citrate treatments, these results suggest that the release of K from soil fractions to the Ca resin was regulated by the nonexchangeable K in both kaolinitic and

smectitic soils. Wang et al. (2004) suggested that the release of K near the threshold of critical K would be controlled by the amount of exchangeable and nonexchangeable K and indicated that the ease of K release increased with a high content of exchangeable K in the soil. As indicated in Eq. [1], the plant removal of K was corrected for the changes in exchangeable K before and after each plant growth period, and is reported as cumulative nonexchangeable K release.

Modeling Potassium Release from Soil Fractions to Calcium Resin

The estimated parameters of the equations describing the rate of release of K from each of the experimental soils are shown in Table 2. The fitted coefficient b of the diffusion equation and coefficients a and b of the power function appear to have little physical or chemical significance other than the statistical fit. The coefficients of the segmented straight line, however, might be a quantification of the two-phase release of K reported by Mengel et al. (1998) and Benipal et al. (2005). We suspect that the coefficients might be proportional to the K release that occurs to plants since the model seemed to fit the release of K both to Ca resin and to plants in the K exhaustion studies. Our results show that the power function and segmented straight line equations more reliably described the release of K in the soils studied than did the parabolic diffusion function (Table 2). The better fit of the power function and segmented straight line equations to the experimental data is indicated by the lower RMS in Table 2. The segmented straight line equation gave the lowest RMS among the equations, except for the Cd and possibly the Ln soils.

Our results are consistent with previous findings (Mengel and Uhlenbecker, 1993; Jalali, 2005). Havlin et al. (1985) indicated that the power function equation adequately described the release of K to Ca resin between 0 and 7000 h. It is unclear

Table 2. The release of K in eight soils to Ca resin as fitted by the parabolic diffusion, power function, and segmented straight line equations and residual mean square (RMS).

Soil series	Parabolic diffusion ($y = bt^{1/2}$)		Power function ($y = at^b$)			Segmented straight line [$y = b_1 \min(\text{node}, x) + b_2 \max(\text{node}, x) - b_2 \text{node}$]			
	b	RMS	a	b	RMS	node	b_1	b_2	RMS
Kaolinitic soils									
Phu Sana	0.81	9.70	5.84	0.16	0.49	60.0	0.20	0.01	0.037
Satuk	0.41	0.99	1.05	0.34	0.87	60.0	0.078	0.00947	0.27
Warin	0.46	2.61	2.67	0.20	0.57	60.0	0.107	0.00698	0.16
Pak Chong	1.24	22.2	8.63	0.17	0.59	74.0	0.282	0.0118	0.097
Smectitic soils									
Lop Buri	2.76	27.1	7.77	0.32	2.04	74.1	0.489	0.0522	0.711
Chai Badan	6.34	283.	26.4	0.26	1.68	74.7	1.24	0.0924	9.60
Takhli	1.29	4.62	2.96	0.36	1.83	68.1	0.226	0.0284	0.50
Lam Narai	1.30	17.2	7.01	0.21	0.32	68.2	0.286	0.0174	0.44

whether a segmented straight line might assist in the interpretation of those data.

The reliability of the K release rate has been examined by considering its relationship with total plant K uptake and yield (Havlin et al., 1985; Mengel and Uhlenbecker, 1993). In addition, the cumulative Ca-resin-extracted K (at 600 h) by all equations and total plant K uptake were closely related, as indicated by a linear regression (Table 3). The laboratory studies indicated that the segmented straight line equation generally provided the best fit describing the release of K and different patterns of K release in kaolinitic and smectitic soils. In addition, the equation provides estimates of a slow and fast release rate, as postulated by others.
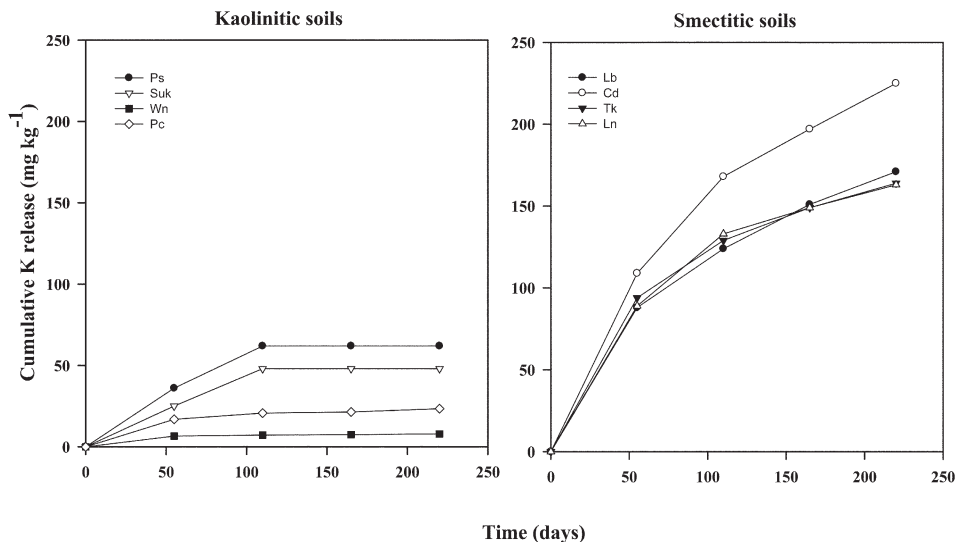

Fig. 2. Cumulative non-exchangeable K release from the eight soils to maize plants at 0 to 220 d. Soils: Ps, Phu Sana; Suk, Satuk; Wn, Warin; Pc, Pak Chong; Lb, Lop Buri; Cd, Chai Badan; Tk, Takhli; Ln, Lam Narai.

Nonexchangeable Potassium Release from Soil to Maize

The exchangeable K after cropping and K removed in each crop declined as the number of crops increased for all eight soils (Fig. 2). More than 40% of the total plant-available K was released from the K_{nonex} pool. The kaolinitic soils showed classic K deficiency symptoms beginning with the second crop (Ps, Wn, and Suk soils) or the third crop (Pc soil), while smectitic soils only showed deficiency symptoms beginning with the fourth crop (Lb, Cd, Tk, and Ln soils). The cumulative K_{nonex} released (sum of first crop to final crop) from kaolinitic soils (48–91 mg kg^{-1}) was much less than that released from smectitic soils (163–225 mg kg^{-1}). The cumulative K_{nonex} released from Pc and Cd soils was higher than from other kaolinitic and smectitic soils, respectively. These results are consistent with the laboratory experiment; in addition, nearly the same amount of cumulative K_{nonex} release was found in the Lb, Tk, and Ln soils. The Ln and Lb soils had high clay contents, while clay content was low and silt content was high in the Tk soil (Table 1). Therefore, the K_{nonex} of the Tk soil is thought to be released from the weathering of mica in the silt fraction. Plant-available K has been shown to be readily released from the silt fraction, probably because of its high mica concentration (Sadusky et al., 1987; Schindler, 2005).

The cumulative K_{nonex} release from soil to the plant can be predicted from the K release from soil to the Ca resin for smectitic soils using the following regression equation: $y = 61.43 + 3.48x$ (adjusted $R^2 = 0.959$, $P \le 0.05$) (Table 3), where x is the cumulative K release from the soil to the Ca resin and y is the K_{nonex} released to maize. The segmented straight line model provided a slightly higher

adjusted R^2 and a lower RMS than did the other models (Table 3). This relationship holds promise as a step toward a better understanding of K release in smectitic soils and possibly leading to a method to better predict availability.

Estimating the Rate of Nonexchangeable Potassium Release using the Segmented Regression Model and Soil Potassium Exhaustion Data

The amount of K_{nonex} released to each crop of maize (mg kg^{-1}) as a function of time (d) is shown in Fig. 2. For the kaolinitic soils, the amount of K_{nonex} released after the occurrence of K deficiency symptoms was assumed to be zero. The results showed that exhaustion of K_{nonex} in the kaolinitic soils occurred much earlier than in the smectitic soils. Both the rapid and slow release rates of K_{nonex} in smectitic soils were higher than those in kaolinitic soils (Table 4). The rapid and slow K release rates of plant-available K_{nonex} were 0.45 to 0.85 and 0 mg kg^{-1} d^{-1}, respectively, in kaolinitic soils and 1.60 to 1.98 and 0.27 to 0.52 mg kg^{-1} d^{-1}, respectively, in smectitic soils. The release of K_{nonex} from soils is believed to result from the equilibrium between interlattice K and soil solution K (Hanway and Scott, 1957). The results of this study are consistent with the findings by Benipal et al. (2005), and Jalali (2005) indicating two fractions of K, one rapidly and one slowly released.

The rapid release (b_1) of K_{nonex} in kaolinitic soils is believed to be the release of K from trace amounts of illite or vermiculite in the clay fractions (Cox et al., 1999). Slow release

Table 3. Linear regression between cumulative nonexchangeable K release at 220 d in the pot experiment of eight soils (x) and predicted Ca-resin extractable K (y) at 600 h by the parabolic diffusion, power function, and segmented straight line equations.

	Parabolic diffusion ($y = bt^{1/2}$)	Power function ($y = at^b$)	Segmented straight line [$y = b_1 \min(\text{time}, a) + b_2 \max(a, \text{time}) - ab_2$]
Linear regression	$y = 56.00 + 3.42x$	$y = 77.60 + 2.51x$	$y = 61.43 + 3.48x$
Adjusted R^2	0.950**	0.944**	0.959**
Residual mean square	1253	1474	1056

** Significant at $P = 0.01$.

Table 4. The amount of plant K uptake, NH$_4$OAc-extractable K after cropping, and nonexchangeable K release to maize in each crop of the eight soils.

Soil series	Crops	Plant K uptake				NH$_4$OAc-K				Nonexchangeable K released to maize[†]			
		Crop 1	Crop 2	Crop 3	Crop 4	Crop 1	Crop 2	Crop 3	Crop 4	Crop 1	Crop 2	Crop 3	Crop 4
	no.						mg kg^{-1}						
Kaolinitic soils													
Phu Sana	2	54 ± 11[‡]	27 ± 3	–	–	21 ± 3	20 ± 1	–	–	36 ± 20	26 ± 8	–	–
Satuk	2	45 ± 10	23 ± 5	–	–	14 ± 2	14 ± 2	–	–	25 ± 10	23 ± 7	–	–
Warin	2	48 ± 20	30 ± 14	–	–	17 ± 2	16 ± 2	–	–	47 ± 21	29 ± 14	–	–
Pak Chong	3	101 ± 26	43 ± 17	22 ± 2	–	43 ± 11	34 ± 4	32 ± 4	–	37 ± 31	34 ± 4	20 ± 2	–
Smectitic soils													
Lop Buri	4	125 ± 13	78 ± 11	34 ± 28	21 ± 12	102 ± 7	60 ± 7	53 ± 3	52 ± 3	88 ± 26	36 ± 8	27 ± 22	20 ± 11
Chai Badan	4	237 ± 41	182 ± 30	89 ± 31	55 ± 10	247 ± 32	124 ± 5	64 ± 6	37 ± 4	109 ± 60	59 ± 48	29 ± 34	28 ± 18
Takhli	4	89 ± 15	71 ± 18	36 ± 5	18 ± 4	90 ± 11	54 ± 5	38 ± 3	35 ± 5	94 ± 24	35 ± 13	20 ± 4	15 ± 7
Lam Narai	4	102 ± 8	44 ± 8	32 ± 9	23 ± 9	47 ± 3	47 ± 4	31 ± 2	22 ± 5	89 ± 9	44 ± 7	16 ± 6	14 ± 13

† Calculated using Eq. [1]: nonexchangeable K = K removed – (exchangeable K$_{before}$ – exchangeable K$_{after}$).

‡ Standard deviation.

(b_2) of K$_{nonex}$ in kaolinitic soils was not detected because these soils are highly weathered and contain no primary minerals such as feldspars.

In the smectitic soils, the rapid release (b_1) of K$_{nonex}$ was probably from illite or vermiculite clay minerals. The slow K release in the smectitic soils has been attributed to clay-fraction K and K-feldspar weathering in the sand and silt fractions (Simard et al., 1992; Sadusky et al., 1987). The marked differences in the slow K release rate in Cd and Lb soils probably resulted from the distribution of total K in these two soils. The Lb soil contained most of its K (50.6% of total K) in the silt fraction, compared with 29.6% in the silt fraction of the Cd soil. The greater amount of slow-release K in the Cd soil probably resulted from the high K content in the clay fraction (27% of K), while the Lb soil contained only 10% of its K in the clay fraction.

Multiple regression analysis relating the rapid (b_1) and slow (b_2) release rates of K$_{nonex}$ with selected initial soil properties resulted in the following equations:

$$b_1 = 0.380 + 0.023(\text{CEC}) + 0.00008(\text{NH}_4\text{OAc-extractable K})$$
$$\text{adjusted } R^2 = 0.834, \ P \leq 0.01 \quad [10]$$

$$b_2 = -0.045 + 0.008(\text{CEC}) + 0.0003(\text{NH}_4\text{OAc-extractable K})$$
$$\text{adjusted } R^2 = 0.925, \ P \leq 0.01 \quad [11]$$

The results suggest that the release rates of K$_{nonex}$ from the experimental soils can be predicted from the soil CEC and initial NH$_4$OAc-extractable K values with reasonably good results. Over the long term, the slow release of K$_{nonex}$ may not provide sufficient K for optimum crop yield. Fertilizer K application would be needed for economic plant production when the release rate of K$_{nonex}$ in the soil is less than the rate of K uptake by the plant.

CONCLUSIONS

The study of K release by successive equilibration with a Ca resin indicated that a larger quantity of available K was found in smectitic than kaolinitic soils. A segmented regression model gave the best characterization of soil K release to the Ca resin and of K$_{nonex}$ release to plants in the K exhaustion greenhouse studies. It provided estimates of two fractions of plant-available K$_{nonex}$, which were released in different patterns and at different rates in kaolinitic and smectitic soils. The rapid and slow K release rates of plant-available K$_{nonex}$ in the greenhouse K exhaustion study were 0.45 to 0.85 and 0 mg kg^{-1} d^{-1}, respectively, for kaolinitic soils and 1.60 to 1.98 and 0.27 to 0.52 mg kg^{-1} d^{-1}, respectively, for smectitic soils. The release rates of plant-available K$_{nonex}$ in the soils studied were affected by clay mineral type, clay content, and CEC.

Our study clearly showed that, for kaolinitic soils, exchangeable K methods such as NH$_4$OAc were adequate to assess K reserves and to predict K fertilizer requirements. In contrast, NH$_4$OAc and Ca resin extractions appear to be necessary to assess K reserves in smectitic soils.

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