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# Potassium release rates from ustisols and their application

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*Key words:* corn, K release rate, kinetics, soil K-supplying power

**Abstract**

Second-order equations were used to characterize the potassium release rate for 20 low-hilly ustisols derived from Quaternary red clay in Zhejiang province, China. This was done under the condition of electric field strength of 44.4 and 88.8 V cm$^{-1}$. The values of the initial K release rate ($\upsilon_0$) ranged from 1.17 to 21.23 and from 1.93 to 61.58, with an average of 5.36 and 9.54 mg kg$^{-1}$ min$^{-1}$ under the electric field strength of 44.4 and 88.8 V cm$^{-1}$, respectively. Six indices, including the relative grain yield, relative total dry matter yield and K uptake in NP treatments of 20 corn field experiments and available K, $HNO_3$ soluble K and slowly available K of soils were used to assess the practical applicability of K release rates. The correlation analysis showed that $\upsilon_0$ was very significantly correlated ($P = 0.01$) with the above six indices, and their correlation coefficients were 0.6275**, 0.5645**, 0.6624**, 0.7277**, 0.7843** and 0.6299**, respectively, under the electric strength of 44.4 V cm$^{-1}$. The $\upsilon_0$ was related to relative total dry matter yield ($P = 0.05, r = 0.5445^*$) and very significantly correlated to the other five indices (relative grain yield, K uptake in NP treatment, available K, $HNO_3$ soluble K and slowly available K), with the correlation coefficients of 0.6064**, 0.7216**, 0.7523**, 0.8202** and 0.6686**, respectively, under the electric strength of 88.8 V cm$^{-1}$. From the results, we conclude that $\upsilon_0$ can be used to estimate the supplying power of soil K to annual crops such as corn, and to characterize soil K fertility.

## Introduction

Potassium is a dynamic element in soil environments. Fertilization and crop growth often make soil K in an unbalanced state due to effects on soil K release (Sparks and Huang, 1985). The questions of how soil K is released into solution and what rate the element is released, are of great importance to the plant nutrient availability and crop production (Havlin and Westfall, 1985). The methods for soil K release mainly include the miscible displacement as reported by Sparks et al. (1980) and Lopez-Pineiro and Garlia Navarro (1997); resin displacement as reported by Martin and Sparks (1983); electro-ultrafiltration (EUF) by Grimme (1980, 1982) and Lu Xiaonan and Lu Yunfu (1992); and as well as the sequential and repeated extraction with various chemical extractants (Cox and Joern, 1996; Cox et al., 1997; Meyer and Jungk, 1993; Zhu and Luo, 1993). The EUF method is a non-equilibrium method extracted with water (Grimme, 1982) which differs from most other methods. Sparks (1980) even studied the apparent K desorption coefficient with first-order equation using K saturated soil (Sparks et al., 1980), and Martin and Sparks (1983) studied the nonexchangeable K release rate with H-saturated resin. Cox and Joern (1997) studied the relationship of K release to particle size. Grimme (1979, 1982) and Lu Xiaonan and Lu Yunfu (1992) described the kinetics of K desorption from soils in a constant electric field of electro-ultrafiltration (EUF), and then obtained the K release rate from the second-order equation, but did not apply rate parameters to crop production and soil fertility estimation. Among the above methods, the EUF method established itself as a useful tool for the evaluation of K release in soil environment.

Havlin and Westfall (1985) established the relationships between K release constants of power equa-

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tion and soil K contents and alfalfa yield in a greenhouse experiment. Mengel and Uhlenbecker (1993) studied the relationships of the *b* values in parabolic diffusion, power, and Elovich equations to K uptake by ryegrass in pot experiments. Then concluded that the *b* value can be used as a reliable indictor for K availability. Lopez-Pineiro and Garlia Navarro (1997) also found that the *b* values in Elovich equation were closely associated with K uptake by forage in pot experiments.

Owing to the complexity of soil K release there still is not a simple and convenient method to obtain the parameter of K release rate. Therefore, most research is confined to simulating in laboratory or greenhouse experiments which have not been comprehensively applied in practice. There have been notably few reports on K release rates from soil, especially those that examine relationships between K release rate and crop response to fertilizer K and native soil K.

The purposes of this paper are to: characterize K release rate in an EUF constant electric field with second-order equations; establish the rate equations of soil K release and calculate the parameters of K release rates; describe the relationships of K release rate to corn yield and K uptake as well as soil K fertility; and explore the practical application for the parameters of K release rates.

## Materials and methods

### *Soils used and experiments conducted*

Twenty field experiments of soil K on corn were conducted at Dongyang, Yiwu, Jihhua, Lanxi and Quzhou county in the hilly red soil region of Zhejiang Province, China. The ustisols used for the experiments were derived from Quaternary red clay. According to the results of X-ray diffraction analysis, the minerals in the surface soils (0–15 cm) are similar and dominated by kaolinite and halloysite, with a small amount of chlorite and illite. Soil pH was determined with a 1:1 soil-to-water ratio; organic matter was determined by $K_2Cr_2O_7{\cdot}H_2SO_4$ digestion, total nitrogen was digested with potassium sulfate–catalyst mixture and determined with Kjeldahl method, CEC (cation exchange capacity) was determined by leaching with 1 *M* $NH_4OAc$, available K was extracted with 1 *M* $NH_4OAc$ and determined by atomic absorption spectrophotometer, $HNO_3$-soluble K was extracted with 1 *M* boiling $HNO_3$ for 10 min and determined by atomic absorption spectrophotometer, and clay was determined by hydrometer method (Lu Rukun, 1999). The soil properties for 20 experiment soils are list in Table 1. The field experiment was carried out 4-fold with two treatments of NP and NPK (urea, calcium phosphate, and KCl were used) and the rates of N is 187.5 kg ha$^{-1}$, P 33.3 kg ha$^{-1}$, and K 125 kg ha$^{-1}$, respectively. The size of each plot was 120 m$^2$ and 120 corn plants were established in each plot. The quantities of K adsorbed by corn were calculated by multiplying the K contents in corn seed and stalk by the corresponding yields. The yields and K uptake of corn for the 20 experiments are shown in Table 2.

### *Determination of K release*

The Electro-ultrafiltration equipment (Vogel Model 724, made in Germany) was used in this study. Key points for the operation procedure of EUF are that K desorption was conducted continuously with 5.0 g soil for 40 min at 25 °C under the voltage of 200 and 400 V, respectively, and the extracts were collected every 5 min for the measurement of K content. The spacing between the cathode and anode in the EUF reaction vessel is 4.5 cm, so the soil solution was subjected to an electric field strength (electric pressure/distance between cathode and anode) of 44.4 and 88.8 V cm$^{-1}$, respectively.

## Results and discussion

### *Rate equation and theoretical calculation of the rate parameter*

K desorption from soils in a constant electric field can be described by a second-order equation (Grimme, 1980, 1982; Lu Xiaonan and Lu Yunfu, 1992). Since the concentration of the desorbable quantity in the reaction vessel is not known, it is reasonable to use the extent of reaction as dependent variable. The equation then reads:

$$\frac{\mathrm{d}d}{\mathrm{d}t} = k(D - d)^2, \tag{1}$$

where $D$ is the maximum desorbable quantity of K in the soil (mg kg$^{-1}$), d the quantity of K desorbed at time $t$ (mg kg$^{-1}$), $t$ the desorption time and $k$ the rate constant of the second-order equation. After integrating and solving for $d$, the equation reads:

$$d = \frac{D \cdot t}{t + \frac{1}{kD}} \tag{2}$$

*Table 1.* Some properties of soils used in corn experiments

| No. | Experiment Location (County) | pH | Organic matter ($g\ kg^{-1}$) | Total nitrogen ($g\ kg^{-1}$) | Clay ($g\ kg^{-1}$) | CEC ($cmol\ kg^{-1}$) | Avail -able K ($mg\ kg^{-1}$) | $HNO_3$ -soluble K ($mg\ kg^{-1}$) | Slowly avail -able K ($mg\ kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| 2–01 | Jianhua | 5.50 | 15.8 | 1.00 | 404.0 | 10.30 | 104 | 280 | 176 |
| 2–05 | Dongyang | 6.01 | 17.8 | 1.01 | 247.5 | 8.37 | 192 | 505 | 313 |
| 2–09 | Quzhou | 4.97 | 14.8 | 0.94 | 233.2 | 7.48 | 68 | 256 | 188 |
| 2–10 | Yiwu | 5.24 | 13.4 | 0.85 | 406.6 | 13.90 | 160 | 364 | 204 |
| 2–15 | Yiwu | 6.55 | 18.9 | 1.16 | 340.3 | 10.00 | 190 | 414 | 224 |
| 3–02 | Dongyang | 6.12 | 15.9 | 0.87 | 153.1 | 6.41 | 255 | 560 | 305 |
| 3–04 | Dongyang | 5.33 | 20.1 | 1.16 | 184.6 | 7.35 | 75 | 306 | 231 |
| 3–05 | Dongyang | 4.90 | 11.5 | 0.70 | 353.4 | 12.10 | 198 | 348 | 150 |
| 3–06 | Dongyang | 6.38 | 11.8 | 0.76 | 157.3 | 6.35 | 80 | 248 | 168 |
| 3–10 | Jianhua | 5.11 | 19.4 | 1.08 | 208.2 | 7.35 | 40 | 210 | 170 |
| 3–11 | Yiwu | 6.18 | 16.1 | 0.92 | 180.2 | 6.95 | 84 | 270 | 186 |
| 3–12 | Yiwu | 5.35 | 13.0 | 0.76 | 423.6 | 9.89 | 139 | 280 | 141 |
| 3–13 | Yiwu | 6.78 | 13.1 | 0.98 | 214.0 | 7.64 | 168 | 331 | 163 |
| 3–14 | Yiwu | 5.93 | 17.6 | 12.6 | 351.4 | 9.30 | 136 | 279 | 143 |
| 3–15 | Yiwu | 5.20 | 19.0 | 1.15 | 280.9 | 10.20 | 82 | 293 | 211 |
| 3–16 | Quzhou | 5.15 | 6.60 | 0.40 | 166.6 | 7.44 | 34 | 123 | 89 |
| 3–17 | Quzhou | 5.20 | 12.6 | 0.77 | 395.3 | 12.40 | 204 | 380 | 176 |
| 3–20 | Lanxi | 6.11 | 11.6 | 0.66 | 182.1 | 7.21 | 68 | 295 | 227 |
| 3–22 | Lanxi | 5.51 | 9.70 | 0.50 | 348.4 | 8.88 | 59 | 155 | 96 |
| 3–23 | Lanxi | 5.01 | 9.10 | 0.51 | 499.4 | 9.15 | 51 | 194 | 143 |

Slowly available K = $HNO_3$–soluble K – Available K.

In order to estimate the relationship between quantity of K desorbed and time, half-time ($t_{1/2}$) was used to denote the time elapsed when the quantity of K desorbed has come to up 50% of the maximum desorbable quantity, this time is defined as the $t_{1/2}$ of soil K desorption. From the Equation (2), we may obtain

$$t_{1/2} = \frac{1}{kD} \tag{3}$$

By combining Equations (2) and (3), we obtained an expression which gives the quantity K desorbed at time $t$.

$$d = \frac{D \cdot t}{t + t_{1/2}} \tag{4}$$

Equation (4) contains two constants, $D$ and $t_{1/2}$, which depend on the properties of the soil itself, but can be calculated by using a liner transformation of Equation (4). The most suitable one is found to be:

$$\frac{t}{d} = \frac{t}{D} + \frac{t_{1/2}}{D} \tag{5}$$

The derivation of Equation (4) may also yield an expression for the desorption or release rate as a function of time.

$$v = \frac{\mathrm{d}d}{\mathrm{d}t} = \frac{D \cdot t_{1/2}}{(t + t_{1/2})^2} \tag{6}$$

Equation (6) provides the desorption rate as a function of time, and it may be used to estimate the desorption rate of K at any time. Those equations mentioned above are available for calculating K desorption rate.

The relationships between the quantity of K desorbed from soil No. 2-0 1 at the electric field strength

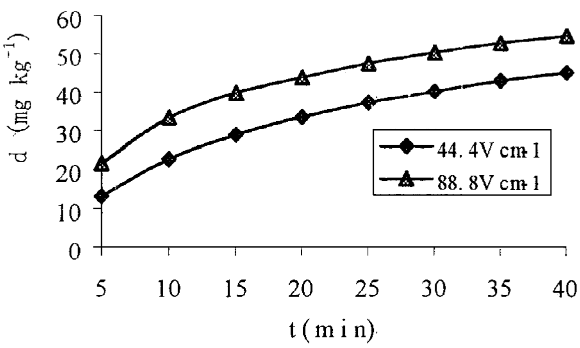


*Figure 1.* The quantity of K desorption as a function of time.

*Table 2.* Main results of corn field experiments

| No | Grain yield ($kg\ ha^{-1}$) | | Total dry matter yield ($kg\ ha^{-1}$) | | Relative yield of grain (%) | Relative yield of total dry matter (%) | K uptake in NP treatment ($kg\ ha^{-1}$) |
|---|---|---|---|---|---|---|---|
| | NPK | NP | NPK | NP | | | |
| 2-01 | 4412.3 | 4076.3 | 13131.8 | 9900.0 | 92.4 | 75.4 | 96.5 |
| 2-05 | 4959.8 | 3815.3 | 10208.3 | 9891.8 | 96.9 | 85.4 | 92.3 |
| 2-09 | 5552.3 | 3709.5 | 15162.0 | 11211.8 | 66.8 | 73.9 | 82.3 |
| 2-10 | 4046.5 | 4002.0 | 13589.3 | 12110.3 | 98.9 | 89.1 | 109.4 |
| 2-15 | 6741.0 | 5697.8 | 14216.3 | 11802.2 | 84.5 | 83.0 | 140.7 |
| 3-02 | 6849.8 | 6363.5 | 15294.0 | 13420.5 | 92.9 | 87.8 | 237.3 |
| 3-04 | 5002.5 | 3577.5 | 10497.0 | 7225.5 | 71.5 | 68.8 | 59.3 |
| 3-05 | 4238.3 | 4050.0 | 9401.3 | 8427.0 | 95.5 | 89.6 | 101.1 |
| 3-06 | 4025.3 | 3769.5 | 11458.5 | 10023.0 | 93.6 | 87.5 | 74.7 |
| 3-10 | 5222.3 | 3654.8 | 14119.5 | 8778.8 | 70.0 | 62.2 | 81.2 |
| 3-11 | 5775.0 | 4520.3 | 15887.3 | 12330.5 | 78.3 | 77.6 | 74.6 |
| 3-12 | 3804.8 | 3280.5 | 13804.5 | 11705.3 | 86.2 | 84.8 | 67.5 |
| 3-13 | 6309.0 | 5819.5 | 17201.3 | 14594.3 | 92.2 | 85.7 | 191.7 |
| 3-14 | 4875.0 | 4200.0 | 14625.0 | 13025.3 | 86.2 | 89.1 | 146.9 |
| 3-15 | 3661.5 | 2918.3 | 9183.0 | 7080.8 | 79.7 | 77.1 | 48.9 |
| 3-16 | 5995.5 | 3440.3 | 13595.3 | 7871.3 | 57.4 | 57.9 | 40.5 |
| 3-17 | 4025.3 | 3450.0 | 9916.5 | 8991.8 | 85.7 | 90.7 | 168.8 |
| 3-20 | 5772.8 | 4216.5 | 12653.3 | 9926.3 | 73.0 | 78.4 | 57.3 |
| 3-22 | 5825.3 | 4100.3 | 15607.5 | 11892.0 | 70.4 | 76.2 | 73.3 |
| 3-23 | 4562.3 | 3375.0 | 10869.8 | 8077.5 | 74.0 | 74.3 | 50.6 |

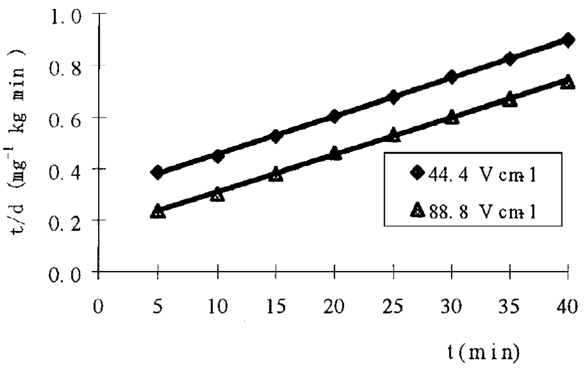


*Figure 2.* The $t/d - t$ equation for K desorption.

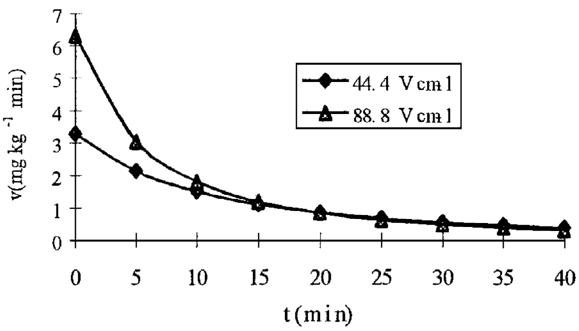


*Figure 3.* Relationship between K release rate and time.

of 44.4 and 88.8 V $cm^{-1}$ and $t$ is illustrated in Figure 1. If the K desorption follows the second-order kinetics, the equation $t/d = t/d + t_{1/2}/d$ obtained after linear transformation of curve in Figure 1 should be a straight line (Figure 2). We observed significant linear correlation relationships between $t/d$ and $t$ with correlation coefficients of >0.999 and 0.999 for both electric field strengths. The $t/d - t$ equations of K desorption and their correlation coefficients as well as the constant $D$ and $t_{1/2}$ for the 20 soils used are presented in Table 3. We found that the correlation coefficients are >0.99 for both electric field strengths, and all reached the significant correlation level ($P = 0.01$). This verifies that K desorption from soil under the constant electric field follows second-order kinetics and can be described by the equation $t/d = t/d + t_{1/2}/d$. The equation contains two constants: $D$ and $t_{1/2}$, which can be calculated according to the slope and intercept of $t/d - t$ linear equation

*Table 3.* The $t/d - t$ equations for K release from soils and their parameters

| Soil no. | Electric field strength 44.4 V $cm^{-1}$ | | | | Electric field strength 88.8 V $cm^{-1}$ | | | |
|---|---|---|---|---|---|---|---|---|
| | Equation | $r(n = 8)$ | $D$ (mg $kg^{-1}$) | $t_{t/2}$ (min) | | $r(n = 8)$ | $D$ (mg $kg^{-1}$) | $t_{t/2}$ (min) |
| 2-01 | $t/d = 0.3054 + 0.0147$t | 0.9997 | 68.0 | 20.8 | $t/d = 0.1640 + 0.0143$t | 0.9995 | 69.9 | 11.5 |
| 2-05 | $t/d = 0.1138 + 0.0065$t | 0.9997 | 153.8 | 17.5 | $t/d = 0.0761 + 0.0079$t | 0.9998 | 126.6 | 9.6 |
| 2-09 | $t/d = 0.2476 + 0.0217$t | 0.9995 | 46.1 | 11.4 | $t/d = 0.2851 + 0.0297$t | 0.9955 | 33.7 | 9.6 |
| 2-10 | $t/d = 0.2278 + 0.0079$t | 0.9958 | 126.6 | 28.8 | $t/d = 0.2619 + 0.O082$t | 0.9870 | 122.0 | 25.8 |
| 2-15 | $t/d = 0.2482 + 0.0084$t | 0.9929 | 119.0 | 29.5 | $t/d = 0.0815 + 0.0074$t | 0.9998 | 135.1 | 11.0 |
| 3-02 | $t/d = 0.0471 + 0.0075$t | 0.9998 | 133.3 | 6.3 | $t/d = 0.0163 + 0.0056$t | 0.9999 | 178.6 | 2.9 |
| 3-04 | $t/d = 0.2218 + 0.0182$t | 0.9999 | 54.8 | 11.9 | $t/d = 0.1118 + 0.0199$t | 0.9998 | 50.3 | 5.6 |
| 3-05 | $t/d = 0.1458 + 0.0074$t | 0.9991 | 135.1 | 19.7 | $t/d = 0.0837 + 0.0071$t | 0.9986 | 140.8 | 11.8 |
| 3-06 | $t/d = 0.2099 + 0.0178$t | 0.9999 | 56.2 | 11.8 | $t/d = 0.1244 + 0.0163$t | 0.9999 | 61.3 | 7.6 |
| 3-10 | $t/d = 0.3301 + 0.0357$t | 0.9999 | 28.0 | 9.2 | $t/d = 0.2864 + 0.0336$t | 0.9992 | 29.8 | 8.5 |
| 3-11 | $t/d = 0.2206 + 0.0179$t | 0.9999 | 55.9 | 12.3 | $t/d = 0.1430 + 0.0190$t | 0.9989 | 52.6 | 7.5 |
| 3-12 | $t/d = 0.1666 + 0.0146$t | 0.9988 | 68.5 | 11.4 | $t/d = 0.2110 + 0.0138$t | 0.9998 | 72.5 | 15.3 |
| 3-13 | $t/d = 0.1178 + 0.0063$t | 0.9982 | 158.7 | 18.7 | $t/d = 0.0870 + 0.0075$t | 0.9982 | 133.3 | 11.6 |
| 3-14 | $t/d = 0.1346 + 0.OO9$t | 0.9984 | 111.1 | 15.0 | $t/d = 0.0802 + 0.0110$t | 0.9995 | 90.9 | 7.3 |
| 3-15 | $t/d = 0.3171 + 0.0215$t | 0.9974 | 46.5 | 14.7 | $t/d = 0.1958 + 0.0145$t | 0.9999 | 69.0 | 13.5 |
| 3-16 | $t/d = 0.4649 + 0.0459$t | 0.9964 | 21.8 | 10.1 | $t/d = 0.4480 + 0.0451$t | 0.9999 | 222.0 | 9.9 |
| 3-17 | $t/d = 0.3133 + 0.0086$t | 0.9973 | 116.3 | 36.4 | $t/d = 0.2009 + 0.0076$t | 0.9978 | 131.6 | 26.4 |
| 3-20 | $t/d = 0.2625 + 0.0247$t | 0.9994 | 40.5 | 10.6 | $t/d = 0.2043 + 0.0281$t | 0.9978 | 35.6 | 7.3 |
| 3-22 | $t/d = 0.8542 + 0.0268$t | 0.9973 | 37.3 | 31.9 | $t/d = 0.5164 + 0.034$t | 0.9946 | 29.4 | 15.2 |
| 3-23 | $t/d = 0.4638 + 0.0277$t | 0.9992 | 36.1 | 16.7 | $t/d = 0.3226 + 0.0332$t | 0.9995 | 30.1 | 9.7 |

(Table 3). Once the values of $D$ and $t_{1/2}$ are obtained, the K desorption rate can be calculated at any time according to Equation (6). Figure 3 demonstrates the relationship of K release rate to time for soil No. 2-0 1. It also may be seen from Equation (6) that K desorption rate is the highest when $t = 0$, that is initial rate ($v_0$) or maximum rate ($v_{max}$) for K desorption. It can be seen from Table 4, $v_0$ ranged from 1.17 to 11.23 mg $kg^{-1}$ $min^{-1}$ and had an average of 5.36 mg $kg^{-1}$ $min^{-1}$4 at the electric field strength of 44.4 V $cm^{-1}$, 1.93–61.58 mg $kg^{-1}$ $min^{-1}$ and average of 9.54 mg $kg^{-1}$ $min^{-1}$ at the electric field of 88.8 V $cm^{-1}$.

*Applications for the rate constant of K desorption*

Whether the parameter of K desorption rate can be used in crop management depends on the correlative relationships between K desorption rate, plant growth, and K contents in soils. Six reference indices (Tables 1 and 2) from 20 corn field experiments and the values of soil K were used to estimate the practical application of K desorption rate. The relative grain yield, relative total dry matter yield as well as the K uptake in NP treatments represent the response of corn to K fertilizer and magnitudes depend on the soil fertility itself. Contents of available K, $HNO_3$ soluble K and slowly available K of soils also are good references for soil K fertility status and are common used indicator for the estimation of K-supplying of soil. It can be seen from results in Table 5, that $v_0$ was significantly correlated ($P = 0.01$) with relative grain yield, relative total dry matter yield and K uptake in NP treatment as well as available K, $HNO_3$ soluble K and slowly available K of soils, with the correlation coefficients of 0.6275** 0.5645**, 0.6624**, 0.7277**, 0.7843 * and 0.6299** at the electric field strength of 44.4 V $cm^{-1}$. The $v_0$ was also correlated with relative total dry matter yield ($P = 0.05, r = 0.5445$*) and very significantly correlated with the other five reference standards, with correlation coefficients of 0.6064**, 07216**, 0.7523**, 0.8202** and 0.6686** at the electric field strength of 88.8 V $cm^{-1}$. The results indicated that $v_0$ reflect the K fertilizer response of corn and fertility level of soil K, and could be used as an index to estimate K-supply power of soil.

*Table 4.* The rate equations and the initial rate of K releases

| Soil no. | Electric field strength 44.4 V $cm^{-1}$ | | Electric field strength 88.8 V $cm^{-1}$ | |
|---|---|---|---|---|
| | Equation | $v_0$ (mg (kg min)$^{-1}$) | Equation | $v_0$ (mg (kg min)$^{-1}$) |
| 2-01 | $v$=4414.4/($t$+20.8)$^2$ | 3.27 | $v$=830.9/($t$+115)$^2$ | 6.09 |
| 2-05 | $v$=12691.5/($t$+17.5)$^2$ | 8.79 | $v$=1215.4/($t$+9.6)$^2$ | 13.19 |
| 2-09 | $v$=1525.5/($t$+11.4)$^2$ | 4.04 | $v$=323.5/($t$+9.6)$^2$ | 3.51 |
| 2-10 | $v$=13646.1/($t$+28.8)$^2$ | 4.40 | $v$=2623.5/($t$+26.5)$^2$ | 3.74 |
| 2-15 | $v$=13510.5/($t$+29.5)$^2$ | 4.03 | $v$=1486.1/($t$+11.O)$^2$ | 12.28 |
| 3-02 | $v$=1839.8/($t$+6.3)$^2$ | 21.23 | $v$=517.9/($t$+2.9)$^2$ | 61.58 |
| 3-04 | $v$=1652.l/($t$+11.9)$^2$ | 4.61 | $v$=281.7/($t$+5.6)$^2$ | 8.95 |
| 3-05 | $v$=12661.5/($t$+19.7)$^2$ | 6.86 | $v$=1661.4/($t$+11.8)$^2$ | 11.93 |
| 3-06 | $v$=1633.2/($t$+11.8)$^2$ | 4.76 | $v$=465.9/($t$+7.6)$^2$ | 8.07 |
| 3-10 | $v$=1257.6/($t$+9.2)$^2$ | 3.04 | $v$=253.3/($t$+8.5)$^2$ | 3.50 |
| 3-11 | $v$=1687.6/($t$+12.3)$^2$ | 4.54 | $v$=394.5/($t$+7.5)$^2$ | 7.01 |
| 3-12 | $v$=1780.9/($t$+11.4)$^2$ | 6.01 | $v$=1109.3/($t$+15.3)$^2$ | 4.74 |
| 3-13 | $v$=12967.7/($t$+18.7)$^2$ | 8.49 | $v$=1546.3/($t$+11.6)$^2$ | 11.49 |
| 3-14 | $v$=11666.5/($t$+15.0)$^2$ | 7.41 | $v$=663.6/($t$+7.3)$^2$ | 12.45 |
| 3-15 | $v$=1683.6/($t$+14.7)$^2$ | 3.16 | $v$=931.5/($t$+13.5)$^2$ | 5.11 |
| 3-16 | $v$=1220.2/($t$+10.1)$^2$ | 2.16 | $v$=219.8/($t$+9.9)$^2$ | 2.24 |
| 3-17 | $v$=14233.3/($t$+36.4)$^2$ | 3.20 | $v$=3474.2/($t$+26.4)$^2$ | 4.98 |
| 3-20 | $v$=1429.3/($t$+10.6)$^2$ | 3.82 | $v$=259.9/($t$+7.3)$^2$ | 4.88 |
| 3-22 | $v$=1189.9/($t$+31.9)$^2$ | 1.17 | $v$=446.9/($t$+15.2)$^2$ | 1.93 |
| 3-23 | $v$=1602.9/($t$+16.7)$^2$ | 2.16 | $v$=292.0/($t$+9.7)$^2$ | 3.10 |

*Table 5.* The relationships between K desorption and reference indices

| Reference standards | Electric field strength 44.4 V $cm^{-1}$ | | Electric field strength 88.8 V $cm^{-1}$ | |
|---|---|---|---|---|
| | Regression equation | $r(n = 20)$ | Regression equation | $r(n = 20)$ |
| Relative yield of grain (%) | $y = 66.46 + 27.44 \lg v_0$ | 0.6275** | $y = 65.42 + 20.74 \lg v_0$ | 0.6064** |
| Relative yield of total dry matter (%) | $y = 67.14 + 19.61 \lg v_0$ | 0.5645** | $y = 67.70 + 14.79 \lg v_0$ | 0.5445* |
| K uptake in NP treatment (kg $ha^{-1}$) | $y = 16.93 + 129.49 \lg v_0$ | 0.6624** | $y = 10.40 + 110.32 \lg v_0$ | 0.7216** |
| Available K (mg $kg^{-1}$) | $y = 5.604l+176.9Og v_0$ | 0.7277** | $y = 2.917 + 143.O4 \lg v_0$ | 0.7523** |
| $HNO_3$-soluble K (mg $kg^{-1}$) | $y = 104.12 + 311.7 \lg v_0$ | 0.7843** | $y = 97.02 + 254.96 \lg v_0$ | 0.8202** |
| Slowly available K (mg $kg^{-1}$) | $y = 98.52 + 134.81 \lg v_0$ | 0.6299** | $y = 94.11 + 111.91 \lg v_0$ | 0.6686** |

According to the scatter diagram of $v_0$ to relative grain yield and using the method for the calculation of critical index proposed by Cate and Nelsion (1971), the critical index for $v_0$ was 3.2 and 4.4 at the electric field strength of 44.4 and 88.8 V $cm^{-1}$, respectively. This means that the soils, which $v_0$ are lower than the critical index, will have relative low soil K fertility and high yield response to the fertilizer K. On the contrary, the soil K fertility is relative high and the yield response to fertilizer K is low. For the perspective of fertilizer distribution, fertilizer K should first be used to the soils with low values of $v_0$ so as to obtain the relative high yield and economic effectiveness.

The above study addresses the difficult problem that K release rate can not be obtained with simple and convenient methods. The index of $v_0$ is related to corn growth and K fertility status of soils, and enables the estimation of soil K-supplying and fertilizer K application by using parameters of K release rate. Further, studies are important to integrate theory and the practical applications of soil K release rate in agronomic system.

## Conclusion

K desorption from soils can be well described by the second-order equation and the rate can also be obtained from the linear form of the second-order equation. The values of $v_0$ ranged from 1.17 to 21.23 and from 1.93 to 61.58, with an average of 5.36 and 9.54 mg kg$^{-1}$ min$^{-1}$ at the electric strength of 44.4 and 88.8 V cm$^{-1}$. The index of $v_0$ was closely related to the response of corn to K fertilizer and K fertility level of soils, and these $v_0$ can be used as an index to assess supplying power of soil K.

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