

The difference of potassium dynamics between yellowish red soil and yellow cinnamon soil under rapeseed (*Brassica napus* L.)–rice (*Oryza sativa* L.) rotation

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Abstract To increase the use efficiency of potassium (K) fertilizer, special attention was paid to the dynamics of soil K in the root zone and non-root zone. Difference in K dynamics between yellowish red soil and yellow cinnamon soil under rapeseed (*Brassica napus* L.)–rice (*Oryza sativa* L.) rotation was studied using a rhizobox system. Results showed that soil water soluble K (Sol-K) and exchangeable K (Ex-K) in the root zone of both soils were reduced in the early stage of rapeseed growth. Along with plant growth and K uptake, soil Sol-K in the inner (0–20 mm to root zone), middle (20–40 mm) and outer (40–60 mm) compartments of the non-root zone of yellowish red soil migrated towards the root zone. As a result, soil Ex-K was transformed into Sol-K. The changes in soil Sol-K and Ex-K in the non-root zone of yellow cinnamon soil were similar to yellowish red soil, and soil non-exchangeable K (Nonex-K) in the root zone also decreased significantly. In the early stage of rice growth, waterlogging promoted

diffusion of soil Sol-K from non-root zone to root zone and transformation of Ex-K into Sol-K. Along with the growth of rice and K uptake, soil Ex-K in each compartment of yellowish red soil decreased significantly. Soil Sol-K and Ex-K in the yellow cinnamon soil declined to a certain extent, and then remained unchanged, while soil Nonex-K kept on decreasing. It revealed that the plants first absorbed K in the root zone, of which K reserve was replenished by a gradual diffusion of K from the non-root zone. The closer to the root zone, the greater the contribution to K uptake by plants. Within one rotation cycle, Ex-K and Sol-K in yellowish red soil were the main forms of K available to the plants, and little Nonex-K could be absorbed. However, in the yellow cinnamon soil, Nonex-K was the main form of K available to the plants, followed by Ex-K and Sol-K.

Keywords Non-root zone · Potassium · Rhizobox · Rhizosphere · Root zone · Soil

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Introduction

Paddy-upland rotations are the most important cropping systems in southern and eastern Asian countries including Bangladesh, China, India, Nepal and Pakistan, covering an estimated area of 26.7 million hectares (Timsina and Connor 2001). In China, these systems are mainly located in the Yangtze River Basin with over 13 million hectares (Dawe et al. 2004). Both

rice and the subsequent crop remove enormous amounts of potassium (K), resulting in a significant negative K balance in soils, even though K fertilizers are applied at recommended doses (Blake et al. 1999; Singh et al. 2003). Consequently, soil K deficiency in paddy fields is becoming one of the key limiting factors for sustainable agricultural production (Cakmak 2002; Sheldrick et al. 2003). In addition, consumption of K fertilizers is increasing, while limited potash resources are available in China (Sheldrick et al. 2003). Therefore, it is very important to apply the fertilizers in an effective way to minimize loss and improve the nutrient use efficiency.

Efficiency of K fertilizer application is affected by various factors, including soil type, soil original K-supplying capacity, crop varieties, levels of nitrogen (N) and phosphorus (P) (Timsina and Connor 2001; Öborn et al. 2005). On coarse sandy soils, a key issue is to reduce K leaching (Kayser and Isselstein 2005). Askegaard et al. (2003) found a positive correlation between Ex-K and leaching loss. For soils of low to medium K adsorption capacity, it is more effective if K is applied in regular small doses during the growing season (Pal et al. 1999). On the other hand, K fixation on clayey soils may actually limit K availability (Reid-Soukup and Ulery 2002). Potassium applied to clayey soils one time in a rotation may not be at risk of leaching, but rather at risk of K fixation in the sheet silicates (Öborn et al. 2005).

Four forms of soil K have been recognized, and they are structural or mineral K (Min-K), non-exchangeable K (Nonex-K), exchangeable K (Ex-K) and water-soluble K (Sol-K) (Sparks 1987). Ex-K and Sol-K are often considered readily available to plants, while Nonex-K and Min-K are only slowly or potentially available (Pal et al. 1999). Dynamic equilibrium reactions exist between the phases of soil K (Sparks 1987). The degree of crop response to K fertilizer is mainly determined by soil K fertility. Because soil Nonex-K may become available to crops, the soil K supplying power can be determined by the amount of Ex-K and Nonex-K in soils (Askegaard et al. 2004). Generally, the effect of applying K fertilizer tends to be more significant when soil Ex-K was lower than the critical level. The absence of crop response to added K in some soils can be attributed to the progressive release of K from the non-exchangeable fraction in the soil (Niebes et al. 1993).

The interaction between K and crop performance varied drastically due to differences in K requirement and acquisition potential for K from the soil between plant species and varieties (Clement-Bailey and Gwathmey 2007). The K absorbing characteristics of crops also need to be considered for rational fertilization within a crop rotation. Combined application of K and N had a remarkable positive reciprocal effect on crops, and was an important approach in improving K use efficiency (Askegaard et al. 2004).

It has been pointed out that K transport from the bulk soil to the root occurs mainly via diffusion in soil solution, a process driven by K^+ concentration gradient between the root surface and the adjacent soil (Hinsinger 1998; Gregory and Hinsinger 1999). To increase the use efficiency of K fertilizer, much attention should be given to the concrete application techniques, such as optimizing timing, method and placement of fertilizer application (Zhang et al. 2004). In this study, a rhizobox experiment was carried out. In the experiment, crops were planted on soils in the centre compartment. No K fertilizer was applied. Special attention was paid to the dynamics of soil K in the root zone and non-root zone under a rapeseed–rice rotation. The objectives of this study were: (1) to investigate the effect of crop growth on K dynamics in root-zone and non-root-zone soils; (2) to compare the difference of K dynamics in different soils; (3) to provide evidence for a soil K supplying mechanism and rational K nutrient regulation in the root zone.

Materials and methods

Source of soils

Plough layer soils (0–20 cm) were taken from two paddy fields in southern China. These two soils were yellowish red soil (Argi-Udic Ferrosols) in Changsha, Hunan province, and yellow cinnamon soil (Xanthic Ali-Udic Cambosols) in Xiangfan, Hubei province. The texture of the yellowish red soil was clay loam, and the soil was derived from Q_2 red clay parent materials. The texture of the yellow cinnamon soil was clay, and the soil was derived from Q_3 loess parent materials (Gong et al. 2003). The soil samples were air-dried, and sieved to 2 mm to remove gravel and debris. General properties of the soils are listed in Table 1 and Fig. 1.

Table 1 Physical and chemical properties of the soils

| Soil type | pH | Organic matter (g kg ⁻¹) | Concentration of different forms of K (mg kg ⁻¹) | | | | Sand ^a (g kg ⁻¹) | Silt ^b (g kg ⁻¹) | Clay ^c (g kg ⁻¹) | Dominant clay minerals |
|----------------------|-----|--------------------------------------|--|-------|---------|----------|---|---|---|--|
| | | | Sol-K | Ex-K | Nonex-K | Total K | | | | |
| Yellowish red soil | 5.2 | 21.5 | 62.4 | 143.3 | 141.0 | 14,243.3 | 382.1 | 328.3 | 289.6 | Kaolinite, hydromica, 1.4 nm intergrade minerals |
| Yellow cinnamon soil | 6.9 | 14.9 | 5.5 | 82.8 | 608.8 | 15,930.0 | 210.1 | 388.6 | 401.3 | Hydromica, kaolinite, vermiculite |

^a Particle size (2–0.05 mm)

^b Particle size (0.05–0.002 mm)

^c Particle size (< 0.002 mm)

Experimental design

A rhizobox experiment growing rapeseed (*Brassica napus* L. cv. Huashuang 4) and then rice (*Oryza sativa* L. cv. Liangyoupeijiu) was conducted in a glasshouse. Two factors were studied: soils and cropping (with or without plant). Each treatment had no K application and was replicated four times. In total, 16 rhizoboxes were used.

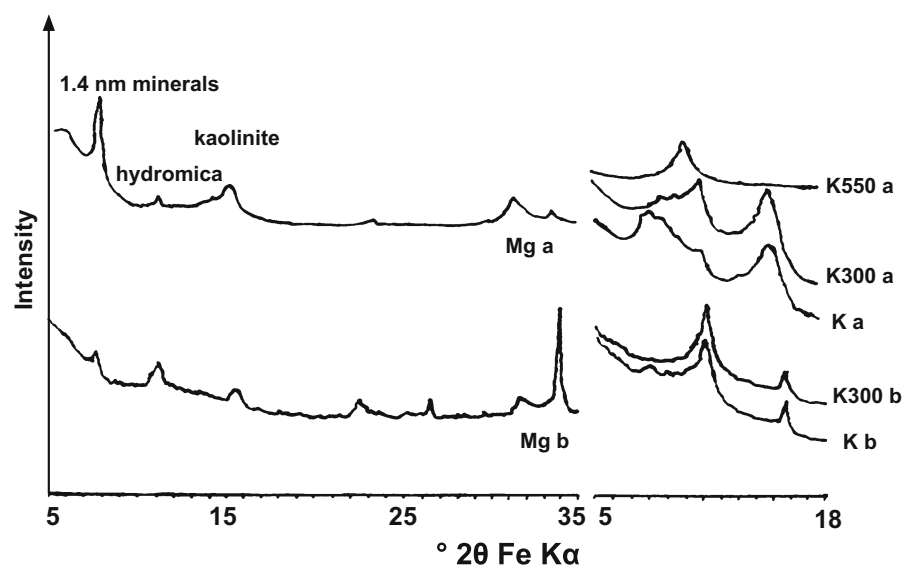
Four kg of dry bulk soil was packed into each rhizobox before sowing rapeseed. N and P fertilizers in the forms of CO(NH₂)₂ and NH₄H₂PO₄ (solid analytical grade) were applied uniformly to the soil at rates equivalent to 0.20 g N kg⁻¹ soil and 0.066 g P kg⁻¹ soil. One-third of the N fertilizer was applied as a basal dose, and the other two-thirds N was divided into two

equal parts and applied as top dressing. All P fertilizer was applied as a basal dose. Fertilization rates and application methods for rice were similar to rapeseed.

Rhizobox installation

A sketch of rhizobox modified from Li et al. (1991) is presented in Fig. 2. In the rhizobox, a 20-mm thick centre contained the root zone compartment where plants were sown. Three 20-mm thick compartments on both sides were non-root zone compartments, named as inner, middle and outer compartments according to the distance to the root zone. Rhizoboxes were jointed together with PVC material. Each compartment was separated with 30 μm aperture nylon mesh.

Fig. 1 X-ray diffraction pattern of original soil fractions: Mg Mg-glycerol saturated, room temperature; K K saturated, room temperature; K300 K saturated, 300°C; K550 K saturated, 550°C (a yellowish red soil; b yellow cinnamon soil)



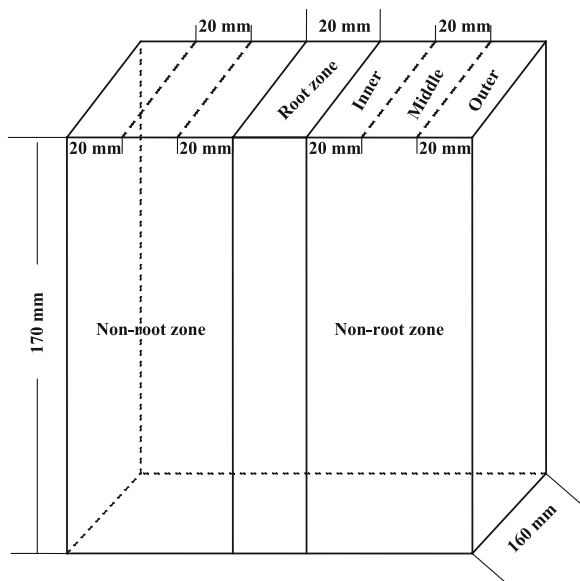


Fig. 2 A sketch map of rhizobox equipment

Plant and water management

For treatments with plants, five rapeseed seeds were sown in the root zone compartment soil, and were thinned to two plants after they reached a height of 5 cm. The rapeseed plants were irrigated with deionized water every 2 or 3 days to maintain the soil water content at 25%. Water additions were determined by repeated weighing of rhizoboxes. The water was poured into the bottom of the box through four pipes erected on the corners. When planting rice, the same numbers of seedlings were applied, but deionized water was poured onto the surface of the boxes until waterlogging.

Soil and plant analysis

Soils were sampled seven times at 1, 77, 153, 178, 263, 292 and 341 days after rapeseed sowing. Ten to 15 g of soil was collected from each compartment using a 450 mm long screw (6 mm in diameter) inserted into the bulk soil and mixed uniformly for testing without air-drying. The defoliation was taken back for drying during the growing stage. Plants above ground were snipped when harvest. Finally, the soil in root zone was gently sieved through a 0.84-mm mesh screen to collect fine root and root hair as much as possible (Vaast and Zasoski 1992).

Sol-K was determined in a 1:10 soil–water extract ratio. Ex-K was determined from the difference between 1.0 mol L⁻¹ NH₄OAc extractable K and water extractable K. Nonex-K in soil was determined from the difference between the boiling 1.0 mol L⁻¹ HNO₃ extractable K and 1.0 mol L⁻¹ NH₄OAc extractable K. Total K was determined by dissolving the soil samples with NaOH (Helmke and Sparks 1996).

Soil pH was measured in water (1:2.5 soil water ratio) using a pH meter. Organic matter was determined by using the dichromate oxidation method (Walkley 1947). Particle size distribution was determined after dispersing 15 g of soil (<2 mm) in 45 mL of 3% hexametaphosphate solution. After dispersion, the soil slurry is sieved through nested standard 0.053-mm mesh sieves to separate sand particles. Clay and silt fractions were determined using the simplified method for soil particle size determination (Kettler et al. 2001). Clay mineralogy of soil was determined by X-ray diffraction method (Huang et al. 2007; Barré et al. 2008). Total K of plant material was determined using the dry ash method in a muffle furnace at 500°C for 2 h. The determination of K in plant and soil samples was performed using a flame photometer.

Statistical analysis

All results were expressed as means with corresponding standard errors and index letters that indicated statistical differences between the means. The means were separated by Fisher's Protected Least Significant Difference (LSD) test at $P < 0.05$. All statistical analyses were completed using SPSS software.

Results

Soil water soluble K

The water soluble K (Sol-K) concentration of yellowish red soil in the treatment without plants increased first, and then decreased during the season of rapeseed growth. It gradually decreased in the rice growth season under rapeseed–rice rotation (Fig. 3a, CK 1). The change of Sol-K in the yellow cinnamon soil was similar to that of yellowish red soil in the season of rapeseed growth. In the season of rice

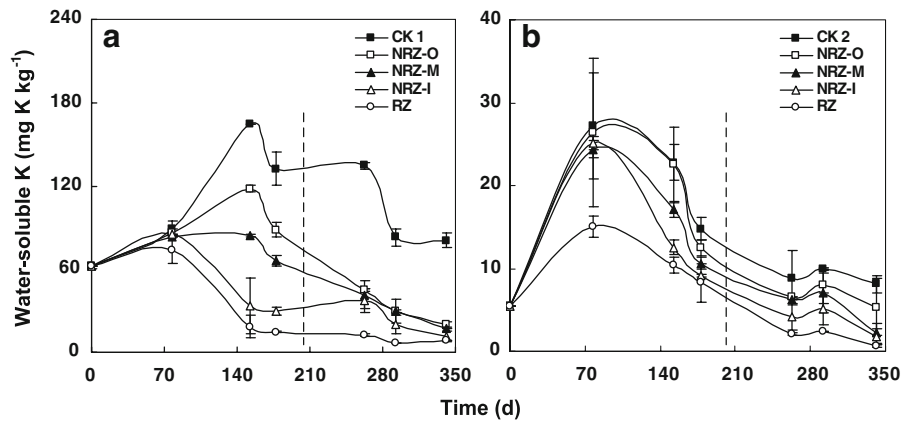


Fig. 3 Dynamics of water-soluble K in root-zone and non-root-zone soils under rapeseed–rice rotation (**a** yellowish red soil; **b** yellow cinnamon soil). *CK 1* control 1, *CK 2* control 2, *NRZ-O* non-root zone outer, *NRZ-M* non-root zone middle, *NRZ-I*

non-root zone inner, *RZ* root zone. The vertical dashed line at abscissa 206 help to distinguish the two crops. The bars on the curves are standard errors for the mean of four replications ($P < 0.05$)

growth, however, the change was insignificant (Fig. 3b, CK 2).

At the early stage of rapeseed growth (77 day after rapeseed sowing), the concentration of Sol-K in yellowish red soil with plants decreased significantly by 17.3% ($P < 0.05$) in the root zone compared with that of the CK 1, and for the non-root zone inner, middle and outer compartment soils they decreased only 4.5%, 6.4% and 3.4%, respectively (Fig. 3a). Yellow cinnamon soil Sol-K concentrations in the root zone and non-root zone inner, middle, outer compartments with plants decreased by 44.9% ($P < 0.05$), 7.6%, 10.3% and 2.7% respectively, compared with that of the CK 2 (Fig. 3b).

At the middle stage of rapeseed growth (153 day after rapeseed sowing), the concentrations of Sol-K in yellowish red soil with plant treatment in the root zone, non-root zone inner, middle and outer compartments were all decreased significantly by 88.7%, 79.6%, 49.0% and 28.4%, respectively, compared with that of the CK 1 ($P < 0.05$). Yellow cinnamon soil Sol-K concentrations in each compartment were similar to yellowish red soil, and were decreased significantly by 54.3%, 45.2% and 24.7% in the root zone, non-root zone inner and middle compartments, respectively, compared with that of the CK 2 ($P < 0.05$).

At the late stage of rapeseed growth (178 day after rapeseed sowing), the concentrations of Sol-K in yellowish red soil with plants in the root zone and non-root zone inner compartment were decreased by 88.9% and 77.7% compared with that of the CK 1, and changed little compared to that of the middle

stage. The decrease in non-root zone middle and outer compartments were 50.4% and 33.5%, which were greater than that of the middle stage. Yellow cinnamon soil Sol-K concentrations were similar to yellowish red soil (each compartment was decreased by 44.3%, 38.5%, 28.2% and 15.5%, respectively).

At the early stage of rice growth (263 day after rapeseed sowing and 57 day after rice sowing), the concentrations of Sol-K in yellowish red soil with plants treatment in the root zone and non-root zone inner compartments were decreased by 90.8% and 72.4%, compared with that of the CK 1, and changed little compared to that of the late stage of rapeseed. The decrease in non-root zone middle and outer compartments were 69.2% and 66.6%, larger than that of the late stage of rapeseed. Yellow cinnamon soil Sol-K concentrations in the root zone and non-root zone inner, middle and outer compartments were decreased by 75.9%, 52.6%, 28.4% and 25.0%, respectively. And the decrease was greater than that of the late stage of rapeseed.

At the middle stage of rice growth (292 day after rapeseed sowing and 87 day after rice sowing), the concentration of Sol-K in yellowish red soil with plants in the root zone was decreased by 91.9%, and the decrease was greater than that of the early stage of rice growth. The decrease in non-root zone inner, middle and outer compartments were 76.1%, 64.3% and 64.0%, respectively, and the sol-K concentration changed little compared to that of the early stage. However, the decrease of soil Sol-K in yellow cinnamon soil changed little compared to that of the early stage.

At the late stage of rice growth (341 day after rapeseed sowing and 131 day after rice sowing), the concentration of Sol-K in yellowish red soil with plants in the root zone was decreased by 89.5% compared with that of the CK 1, and changed little compared to that of the middle stage. The decrease of non-root zone inner, middle and outer compartments were 85.5%, 78.9% and 75.3%, respectively, greater than that of the middle stage. The decrease of soil Sol-K in yellow cinnamon soil changed little compared to that of the middle stage.

Soil exchangeable K

Exchangeable K (Ex-K) concentration of yellowish red soil in the treatment without plants changed little first, and then decreased during the season of rapeseed growth. The change during the rice growth season was similar to the rapeseed season (Fig. 4a, CK 1). A similar pattern of change for the yellow cinnamon soil Ex-K concentration was observed, except during the season of rice growth when the Ex-K was decreased gradually (Fig. 4b, CK 2).

At the early stage of rapeseed growth, soil Ex-K concentrations in the yellowish red soil with plants treatment in the root zone and non-root zone inner compartment were reduced by 16.1% and 6.6%, compared with that of the CK 1 ($P<0.05$) (Fig. 4a). Along with the rapeseed growth and K uptake, soil Ex-K in the middle compartment of the non-root zone was also decreased significantly by 28.1% ($P<0.05$),

and the decrease was greater than that of the early stage (0.3%). At the late stage of rapeseed growth, no change was found in soil Ex-K in each compartment. At the early stage of rice growth, it was discovered that soil Ex-K concentrations in the root zone and non-root zone inner, middle and outer compartments were decreased by 82.0%, 64.5%, 37.3% and 22.8%, respectively, and the decrease was greater than that of the late stage of rapeseed growth (each compartment was decreased by 72.5%, 46.1%, 33.3% and 7.3%, respectively). Along with growth of rice and K uptake, soil Ex-K in each part decreased significantly. At the late stage of rice growth, no change was found in soil Ex-K in each compartment.

For the yellow cinnamon soil, the reduction of soil Ex-K was found only in the root zone at the early stage of rapeseed growth (Fig. 4b). Along with the rapeseed growth and K uptake, the changes of soil Ex-K in each compartment were similar to the yellowish red soil. At the late stage of rapeseed growth, however, soil Ex-K concentrations in each compartment were decreased by 57.5%, 26.5%, 13.4% and 7.6%, respectively, and the decrease was greater than that of the middle stage of rapeseed growth (each compartment was decreased by 45.5%, 18.6%, 11.6% and 7.4%, respectively). At the early stage of rice growth, the change of soil Ex-K was also similar to yellowish red soil. Along with the growth of rice and K uptake, similar to Sol-K, soil Ex-K concentration in each compartment declined to a certain extent, and then remained unchanged, although more K appeared to be absorbed by rice.

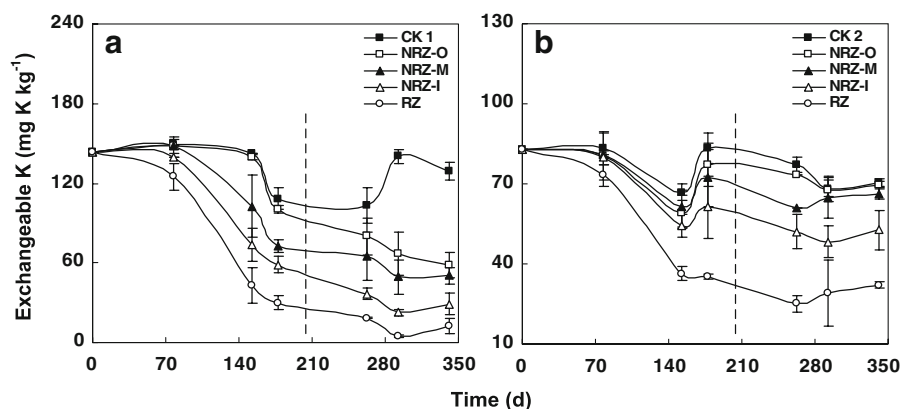


Fig. 4 Dynamics of exchangeable K in root-zone and non-root-zone soils under rapeseed-rice rotation (**a** yellowish red soil; **b** yellow cinnamon soil). CK 1 control 1, CK 2 control 2, NRZ-O non-root zone outer, NRZ-M non-root zone middle,

NRZ-I non-root zone inner, RZ root zone. The vertical dashed line at abscissa 206 help to distinguish the two crops. The bars on the curves are standard errors for the mean of four replications ($P<0.05$)

Soil non-exchangeable K

Soil non-exchangeable K (Nonex-K) concentration in yellowish red soil of the treatment without plants decreased first, and then increased at the stage of rapeseed growth. It gradually decreased in the stage of rice growth under rapeseed–rice rotation (Fig. 5a, CK 1). Soil Nonex-K in each compartment changed little compared to that of CK 1 in whole rotation (Fig. 5a).

The trend of Nonex-K change of the yellow cinnamon soil was similar to that of yellowish red soil in the season of rapeseed growth. However, for rice growth Nonex-K concentration decreased first, and then increased (Fig. 5b, CK 2).

At the early stage of rapeseed growth, soil Nonex-K of yellow cinnamon soil with plants in each compartment had no significant change compared to that of CK 2 (Fig. 5b). Along with the rapeseed growth and K uptake, soil Nonex-K concentrations in the root zone and non-root zone inner compartments were always reduced first. At the late stage of rapeseed growth, soil Nonex-K concentrations in the middle and outer compartments of the non-root zone were decreased significantly. At the early stage of rice growth, soil Nonex-K in each compartment changed little compared to that of the late stage of rapeseed owing to less rice biomass and K uptake. Along with the rice growth and K uptake, soil Nonex-K in each compartment decreased significantly.

Potassium concentrations in plants and K uptake by crops in different forms of K sources

Potassium concentrations in harvested rapeseed plants were significantly higher than that in rice in the both soils (Table 2). This indicated rapeseed needs much more K than rice. It was also observed that K concentrations in the harvested rapeseed and rice plants on the yellow cinnamon soil were lower than that in the yellowish red soil. This may be due to lower available K and organic content in the soil.

The decrease of Sol-K and Ex-K of yellowish red soil in the root zone was significantly greater than that of non-root zone (Table 3). The decrease of Nonex-K in the root-zone soil was similar to that of non-root zone. For yellow cinnamon soil, the changes of Sol-K and Ex-K in the root-zone soil were generally the same as yellowish red soil, but the decrease of Nonex-K in root-zone soil in yellow cinnamon soil was actually significant compared to that of non-root-zone soil.

For the non-root zone of both soils, the closer to the root zone, the greater the decrease of Sol-K and Ex-K (inner>middle>outer). There was no significant difference of Nonex-K in each compartment of the non-root zone of yellowish red soil. For yellow cinnamon soil, however, the same pattern was found for Nonex-K in the non-root-zone soil.

The decrease of soil Ex-K of yellowish red soil was the greatest in each compartment of the rhizobox, followed by soil Sol-K and soil Nonex-K (Table 3). In the whole rotation, the amount of K uptake by crops was

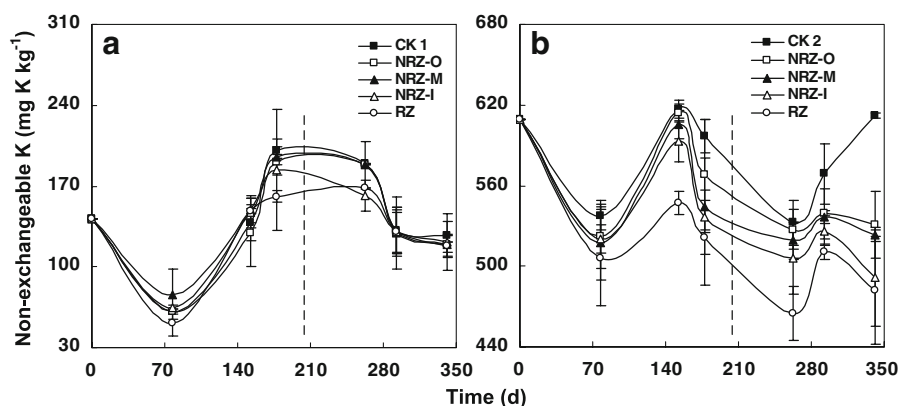


Fig. 5 Dynamics of non-exchangeable K in root-zone and non-root-zone soils under rapeseed–rice rotation (**a** yellowish red soil; **b** yellow cinnamon soil). CK 1 control 1, CK 2 control 2, NRZ-O non-root zone outer, NRZ-M non-root zone middle,

NRZ-I non-root zone inner, RZ root zone. The vertical dashed line at abscissa 206 help to distinguish the two crops. The bars on the curves are standard errors for the mean of four replications ($P < 0.05$)

Table 2 Potassium concentration in harvested rapeseed and rice and K uptake by crops under rapeseed–rice rotation

| Soil type | K concentration (%) | | | | | | | | K uptake (mg pot ⁻¹) | |
|----------------------|---------------------|------|------|------|------|-------|-------|------|----------------------------------|------|
| | Rapeseed | | | | | Rice | | | Rapeseed | Rice |
| | Leaf | Stem | Pod | Seed | Root | Straw | Grain | Root | | |
| Yellowish red soil | 1.82 | 1.79 | 3.12 | 1.13 | 0.18 | 0.45 | 0.34 | 0.12 | 373.7 | 90.5 |
| Yellow cinnamon soil | 0.45 | 0.61 | 3.03 | 0.82 | 0.08 | 0.18 | 0.35 | 0.06 | 173.3 | 47.4 |

464.2 mg pot⁻¹ (Table 2), and was smaller than the value of 644.2 mg pot⁻¹ (Table 3) which was the sum of the decreases of different forms of K in each compartment of soil. For yellow cinnamon soil, the decrease of soil Nonex-K was the greatest, followed by soil Ex-K and soil Sol-K. In the whole rotation, the amount of K uptake by crops was 220.7 mg pot⁻¹, and was also smaller than the sum of all the decreases (475.4 mg pot⁻¹).

Discussion

Influencing factors of soil potassium transformation

A dynamic equilibrium exists between different forms of K in soils (Sparks 1987). Many factors such as soil moisture and fertilizer application affected these equilibrium reactions (Burns and Barber 1961; Zeng and Brown 2000). At the early stage of rapeseed growth, as soil concentration of Sol-K increased,

soil concentration of Ex-K showed no significant change, while soil Nonex-K concentration were decreased in both yellowish red soil and yellow cinnamon soil without plants treatments (Figs. 3, 4 and 5, CK 1 and CK 2). This showed that fertilizer application probably induced the soil K equilibrium be transferred towards Sol-K. Zhou and Huang (2006) pointed out that the application of NH₄H₂PO₄ induced the release of interlayer K in K-bearing minerals. NH₄⁺-N fertilizer could increase the content of soil Sol-K owing to the exchange of NH₄⁺ to K⁺ (Nielsen 1972; Moritsuka et al. 2004). At the late stage of rapeseed growth, soil Sol-K and Ex-K were reduced, and soil Nonex-K was improved. This indicated that the effect of fertilizer on K release was limited. Soil K equilibrium shifted to K fixation. At the early stage of rice growth, there were no significant changes in different forms of K due to the dual effects of waterlogging and fertilizer.

On the other hand, the changes of different forms of K were probably related to the extraction and

Table 3 Concentrations of different forms of K in root-zone and non-root zone soils under rapeseed–rice rotation

| Soil type | Position | Sol-K (mg kg ⁻¹) | | Ex-K (mg kg ⁻¹) | | Nonex-K (mg kg ⁻¹) | | Sum | |
|----------------------|----------|------------------------------|-------|-----------------------------|--------|--------------------------------|--------|-----------------------------|-----------|
| | | Conc. | Dec. | Conc. | Dec. | Conc. | Dec. | Dec. (mg kg ⁻¹) | Prop. (%) |
| Yellowish red soil | CK 1 | 80.6±5.0 a | – | 129.2±6.4 a | – | 127.2±19.2 a | – | – | – |
| | NRZ-O | 19.9±1.9 b | –60.7 | 58.6±9.5 b | –70.6 | 118.7±0.1 a | –8.5 | –139.8 | 21.1 |
| | NRZ-M | 17.0±0.1 b | –63.6 | 50.5±6.2 b | –78.8 | 119.6±7.0 a | –7.6 | –150.0 | 22.6 |
| | NRZ-I | 11.7±3.8 c | –68.9 | 28.8±8.1 c | –100.4 | 121.7±0.1 a | –5.5 | –174.8 | 26.4 |
| | RZ | 8.4±0.1 c | –72.2 | 12.7±5.8 d | –116.5 | 118.2±21.2 a | –9.0 | –197.7 | 29.9 |
| Yellow cinnamon soil | CK 2 | 8.1±1.1 a | – | 70.5±1.4 a | – | 612.3±1.8 a | – | – | – |
| | NRZ-O | 5.3±0.6 b | –2.8 | 69.7±1.3 a | –0.8 | 530.9±8.8 b | –81.4 | –84.9 | 16.8 |
| | NRZ-M | 2.2±1.2 c | –5.9 | 66.3±1.8 a | –4.2 | 523.1±4.3 bc | –89.2 | –99.3 | 19.7 |
| | NRZ-I | 1.7±1.0 c | –6.4 | 52.6±7.4 b | –17.9 | 491.9±36.6 cd | –120.4 | –144.6 | 28.6 |
| | RZ | 0.7±0.1 c | –7.4 | 32.0±1.2 c | –38.5 | 481.9±40.3 d | –130.4 | –176.3 | 34.9 |

Values are means±SE (*n*=4). The different letters following the figures in the same column indicate the significant differences at a *P*<0.05 level

Conc. Concentration, *Dec.* decrease, *Prop.*, proportion, *CK 1* control 1, *CK 2* control 2, *NRZ-O* non-root zone outer, *NRZ-M* non-root zone middle, *NRZ-I* non-root zone inner, *RZ* root zone

determination. For example, soil moisture had important effects on soil K determination (Kuchenbuch et al. 1986). The result may not necessarily reflect the actual process of soil K transformation (Luebs et al. 1956).

Potassium diffusion

The main mechanism of soil K supply is diffusion (Barber 1985). Research has shown that when K fertilizer was applied to the soil, the K concentration in the fertilizer zone was several times higher than rest of the soil, and K moved in the soil through diffusion (Du et al. 2006). In our study, the K concentration gradient arose by growing plant, which was formed when the rate of K uptake exceeded that of K supply from the root-zone soil. The concentration of K in the vicinity of the root surface was lowered in response to plant uptake. The concentration of K in non-root-zone soil was higher than that of the root-zone soil, resulting in gradual K diffusion from non-root zone to the root zone.

At the early stage of rapeseed growth, soil Sol-K and Ex-K in the root zone of both soils were reduced first due to K uptake by rapeseed (Figs. 3 and 4). Along with the rapeseed growth and K uptake, soil Sol-K in the non-root zone was migrating towards the vicinity of the root zone. As a result, soil Ex-K was gradually transformed into Sol-K. At the late stage of rapeseed growth, soil Sol-K concentration in root zone declined to a certain extent, and then remained unchanged, while Sol-K in the non-root zone kept diffusing towards the root zone.

At the early stage of rice growth, waterlogging promoted diffusion of soil Sol-K from the non-root zone to the root zone as well as the transformation of Ex-K into Sol-K. It might be also due to the K uptake by rice.

At the middle stage of rice growth, soil Sol-K in the root zone of yellowish red soil was reduced along with the rice growth and K uptake. Soil Ex-K in each part was also decreased significantly. At the late stage of rice growth, soil Sol-K concentration in root zone and Ex-K in each compartment declined to a certain extent, and then remained unchanged, while Sol-K in the non-root zone kept diffusing towards the root zone. But for the yellow cinnamon soil, the decrease of soil Sol-K changed little compared to that of the early growth stage implying that the main K form

supplied by the soil to rice at this stage might not be soil Sol-K.

For the yellowish red soil, the contribution of soil Nonex-K to crops was limited (Fig. 5). The changes were mainly affected by physiochemical processes such as soil K fixation and release. For the yellow cinnamon soil, however, soil Nonex-K was transformed to Sol-K and decreased significantly, which was absorbed by crops. Hinsinger and Jaillard (1993) obtained similar results in the rhizosphere of ryegrass.

Differences in soil K transformation between yellowish red soil and yellow cinnamon soil

The decrease of soil Sol-K and Ex-K was higher in yellowish red soil than in yellow cinnamon soil under rapeseed-rice rotation. On the one hand, it was owing to higher soil Sol-K (62.4 mg kg^{-1}) and Ex-K concentration (143.3 mg kg^{-1}) of yellowish red soil. On the other hand, it was probably related to dominant clay minerals of 1:1 type. Therefore, the main forms of K supplied by yellowish red soil to the crops were Ex-K and Sol-K, while K from soil Nonex-K was small.

The yellow cinnamon soil used in our study contains hydromicas and vermiculite as dominant clays, which have stronger K fixation capacity. Thus, the concentration of soil Nonex-K was high (Badraoui et al. 1992; Portela 1993). Along with the crops growth and K uptake, soil Ex-K and Sol-K declined to a certain extent, and then remained unchanged. However, soil Nonex-K decreased significantly. There may be a correlation between Nonex-K decrease and clay mineral modifications (Ghosh and Singh 2001; Barré et al. 2007). The modifications of X-ray patterns of the clay fractions from the different compartment soils induced by Nonex-K release will be addressed in another paper. Therefore, it can be concluded that the main form of K supplied by yellow cinnamon soil to the crops was probably Nonex-K, followed by soil Ex-K and Sol-K. These results are in agreement with previous researches (Mitsios and Rowell 1987; Hinsinger 2002).

For the yellowish red soil which is rich in 1:1 type clay minerals, applying K fertilizer should follow the principle of limiting quantity in several applications to avoid leaching loss. For the yellow cinnamon soil which is rich in expanding 2:1 type clay minerals (Hinsinger et al. 1992; Barré et al. 2008),

the application of K fertilizer should be according to the crop requirement because abundant fixation sites can serve as K reserves.

Potassium balance in the soil–plant system

In the whole rotation, the amount of K uptake by crops in yellowish red soil was smaller than the sum of the decreases of different forms of K in each compartment of soil. For the yellow cinnamon soil, the amount of K uptake by crops was also smaller than the sum of all the decreases. It is possible that part of the decrease of soil K may actually correspond to the transformation to 1.0 mol L^{-1} boiling HNO_3 non-extractable K. The error may also probably be caused by systematic errors in extraction and determination of different forms of K. Finally, the gap between K uptake by plants and K removed from K pools must be partly due to the fact that all the fine roots were not recovered. The K leaching was negligible because the rhizobox system is airtight.

In conclusion, under a rapeseed–rice cropping system, yellowish red soil and yellow cinnamon soil varied in their K dynamics. The extent of reduction of soil Sol-K and Ex-K was higher in yellowish red soil compared to that of yellow cinnamon soil. The degree of decrease of soil Nonex-K was significantly lower. These were related to initial soil K concentrations and main clay mineral types. Our results indicated that crops first absorbed K in the root zone, of which K reserve was replenished by gradual K diffusion of K from the non-root zone. The closer to the root zone, the greater the contribution to K uptake by crops. The results from this study can be used for the development and formulation of more precise K fertilizers for certain soils.

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