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A Device for Simulating Soil Nutrient Extraction and Plant Uptake*[1]

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ABSTRACT

In situ evaluating the availability of soil nutrients has been a challenge. In this study, a new type of Device for Simulating Soil Nutrient Extraction and Plant Uptake (DSSNEPU) and its operating procedures were introduced. The device consists of a sampling tube, a fluid supply system, a low pressure system, a tube sheath and an elution cylinder. The sampling tube was firstly soaked in the solution of 0.5 mol L^{-1} $NaHCO_3$ and then buried into soils. The fluid supply system was connected to the sampling tube and the deionized water was supplied. During the period, low pressure system started a vacuum for 3 min every 10 min interval. After extraction, the sampling tube was removed and the nutrients on the sampling tube were eluted with 0.5 mol L^{-1} HCl. The elution solution was used for nutrient measurement. The amounts of P and K extracted by DSSNEPU reached the maximal values after 4 h. No significant increases of P and K were observed for longer extraction duration. The optimal temperature for extracting P and K was 30 °C in this experiment. Extracted P and K were increased by 83.3% and 84.6% with the employment of low pressure system in comparison to those without employing low pressure system. Correlation analysis indicated that P and K extracted by DSSNEPU were highly correlated with those by conventional chemical extraction and by plant uptake. The above results suggest that this device is applicable to assess the availability of nutrients in soils.

Key Words: available nutrients, conventional chemical extraction, ion exchange membrane, low pressure system, soil nutrient evaluation

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INTRODUCTION

The soil nutrient contents are important indices of soil fertility. Measuring the nutrient contents is important for guiding fertilization. The extraction of soil nutrients is the key step for nutrient measurement. Extraction techniques for soil nutrients can be grouped into three methods: chemical extraction, plant assessment and ion exchange resin bead/membrane extraction (Price, 2001; Mallarino and Atia, 2005). Chemical extraction is the conventional method for extracting soil nutrients, which has been widely used for several years. However, chemical extraction method changes the physical and chemical properties of soil greatly (Mengel *et al.*, 2001). Furthermore, chemical extraction is inherently static. The kinetics of nutrient release and movement in soils were not considered in the chemical extraction, which may result in inaccurate estimation of soil available nutrients (Abrams and Jarrel, 1992; Sharpley *et al.*, 2004). Fixen and Grove (1990) pointed out that the extracts for chemical extraction method were not specific to a certain soil type. The plant assessment method seems to be reliable. However, it takes a long time for plant to absorb nutrients from soils. Moreover, the results can be easily affected by many factors such as management techniques, environmental conditions, plant species *etc.*, which will lead to unsatisfactory repeatability. Therefore, it's essential to develop a more accurate, more convenient and more objective method to assess the availability of soil nutrients (Mallarino and Atia, 2005).

Extracting nutrients from soils with ion exchange resin is an *in-situ* extraction method. It resembles closely to the uptake mechanism of plants roots and is superior to the conventional chemical extraction (van Raij, 1994). Skogley *et al.* (1990) invented a soil analysis technique using ion exchange resin in mesh bags called Phytoavailablity Soil Test (PST). With the de-

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vice of PST, Yang *et al.* (1991) found some functional relationships among the amount of extracted nutrients, burial durations and temperatures. Later, Li *et al.* (2001) indicated that ion exchange membrane (IEM) resembled more closely to plant roots than resin beads did in absorbing nutrients from soils. An advanced version of IEM-based extraction device, Plant Root Simulator (PRS^{TM}), was invented by Schoenau *et al.* (1993). PRS^{TM} has been used for soil nutrient test (Qian *et al.*, 1992; Hangs *et al.*, 2002; Greer *et al.*, 2003), the assessment of mineralization of soil organic matter (Qian and Schoenau, 1995) and nutrient release and supply research (Li *et al.*, 2001; Qian and Schoenau, 2007; Sharifi *et al.*, 2009). Though PRS^{TM} is more accurate in the extraction for nutrients test, easier to be inserted into soil and to be cleaned after taking out of soil, there are still some disadvantages. For example it may lose good contact with soil under some extreme conditions. To overcome the disadvantages of the previous IEM-based devices, we invented a set of IEM-based device: the Device for Simulating Soil Nutrient Extraction and Plant Uptake (DSSNEPU). The effects of burial duration, soil temperature, and low pressure system on extracted P and K were examined with the device. Correlations among the nutrients extracted by DSSNEPU, chemical extraction method and plant uptake were also discussed in this paper.

MATERIALS AND METHODS

Soils

The soils used in this study were collected from the upper 20-cm layer of the soil located at South China Agricultural University (23° 10′ 41″ N, 113° 21′ 33″ E), Guangzhou of China. The soils belong to latosolic red soils according to the Genetic Soil Classification of China, which are approximately equal to Ferric Acrisols in the World Reference Base. The soil had the following properties of sand 520.8 g kg^{-1}, slit 423.2 g kg^{-1}, clay 56.0 g kg^{-1}; pH (1:2.5 soil/water) 4.5, CEC 10.61 $cmol_c$ kg^{-1} and organic carbon 2.566 g kg^{-1}. Three treatments were set to represent three levels of soil fertility: low fertility (available P 0.65 mg kg^{-1} and available K 67.0 mg kg^{-1}), medium fertility (available P 3.61 mg kg^{-1} and available K 152.9 mg kg^{-1}) and high fertility (available P 7.95 mg kg^{-1} and available K 230.1 mg kg^{-1}). Soil samples were air-dried, sieved (2 mm) and mixed thoroughly before fertilizers were added. The application of fertilizers to the soil of medium fertility was in quantities of 100 mg N kg^{-1}, 100 mg P kg^{-1} and 100 mg K kg^{-1} in forms of NH_4NO_3, $Ca(H_2PO_4)_2{\cdot}H_2O$ and $K_2HPO_4{\cdot}3H_2O$, respectively. The fertilizers applied to the high fertility soil were doubled those to the medium fertility soil. No fertilizers were added to the soil of low fertility. After air-drying and grinding again, the soil treatments were measured into plastic pots, with every pot containing 1.5 kg of air-dried soil.

Device components

The DSSNEPU device consists of five parts: a sampling tube, a fluid supply system, a low pressure system, a tube sheath and an elution cylinder. The sampling tube is covered by IEM to absorb soil nutrients. The exchange capacities of IEM in this experiment were 1.6 and 2.0 mmol g^{-1} for anion and cation exchange membranes, respectively. The size of IEM on each sampling tube was 5 cm × 20 cm. The upper end of sampling tube connects with a fluid supply system and a low pressure system. The fluid supply system delivers deionized water to the sampling tube and keeps the IEM and rhizosphere soil moist. The low pressure system generates a pressure lower than atmosphere and enhances the movement of soil nutrients. The tube sheath is used to protect the IEM when sampling tube is buried into soil. The elution cylinder is the place for elution after sampling tube is withdrawn from soil. More details about the construction of the DSSNEPU will be discussed in the "RESULTS" section. A schematic diagram of the setup of DSSNEPU is presented in Fig. 1 and the components of DSSNEPU are shown in Fig. 2.

Operation protocols of DSSNEPU

The operation protocols for DSSNEPU can be summarized into 7 steps:

i) Pretreatment: the sampling tube was soaked into 0.5 mol L^{-1} $NaHCO_3$ solution for over 24 h to make the IEM (2, Fig. 2) saturated with Na^+ and HCO_3^-. The solution was changed twice during the process. Then the IEM (2) was rinsed by deionized water to remove the residual $NaHCO_3$ that was not absorbed tightly by IEM (2). The sampling tube was soaked in deionized water before burial.

ii) Burying: the sampling tube was covered by the tube sheath (26) to reduce the friction between IEM (2) and soil during the burial process. The sampling tube was buried into the test soil and the tube sheath (26) was withdrawn. A close contact between IEM and soil should be ensured.

iii) Fluid supply: deionized water was filled into fluid storage bottle. The volume of deionized water was equal to the 90% of field water-holding capacity of

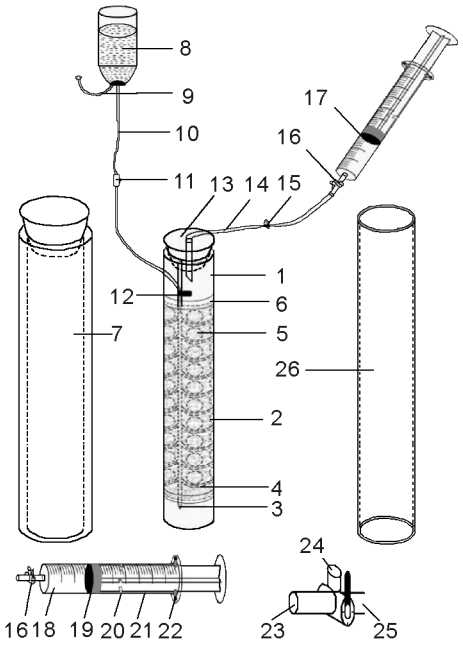

Fig. 1 The setup of the Device for Simulating Soil Nutrient Extraction and Plant Uptake (DSSNEPU). 1: sampling tube frame; 2: ion exchange membrane (IEM); 3: main channel; 4: ring channel; 5: hole; 6: plastic fixation film; 7: elution cylinder; 8: fluid storage bottle; 9: air pipe; 10: fluid pipe; 11: flux controller; 12: dropper; 13: tube stopper; 14: vent pipe; 15: screw clamp; 16: T-cock valve; 17: syringe; 18: barrel; 19: plunger head; 20: notch; 21: plunger shaft; 22: slice; 23: nozzle to sampling tube; 24: nozzle to atmosphere; 25: nozzle to syringe; 26: sheath.

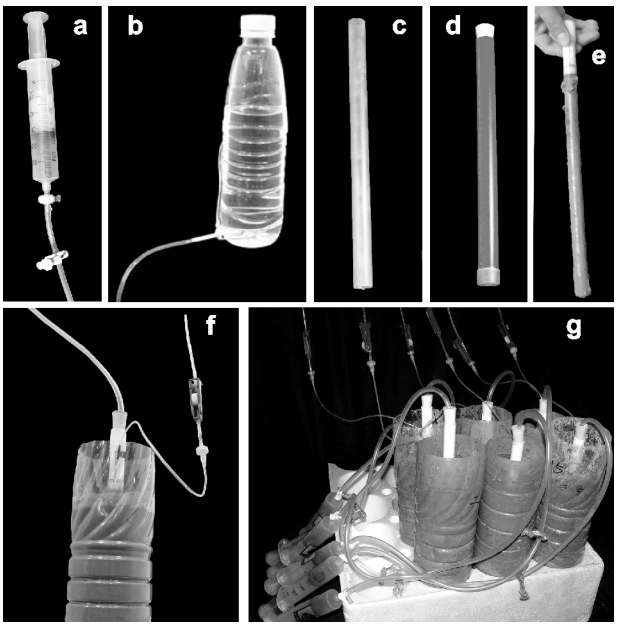

Fig. 2 The main components of the Device for Simulating Soil Nutrient Extraction and Plant Uptake: syringe of low pressure system (a), fluid storage bottle (b), tube sheath (c), elution cylinder (d), sampling tube taken out of soil (e), sampling tube connecting with fluid supply system and low pressure system (f) and the scene of soil nutrient extraction (g).

the test soil. The dropper was inserted at the main channel (3) of sampling tube after the tube had been buried properly. The system was switched on and the deionized water was transported to the channels (3, 4) on the sampling tube. The flux speed of fluid supply system was 1 mL min^{-1}.

iv) Application of low pressure system: the tube stopper (13) was stuffed into the upper end of the sampling tube. The air tightness must be ensured for better extraction effects. The T-cock valve (16) was turned to the position that the system was isolated from atmosphere. The plunger (19) of syringe (17) was pulled to the position of needed graduation and the notch (20) in plunger shaft (21) was gotten stuck by the slice (22) in barrel (18) to fix the plunger. Low pressure condition was formed in the inner space of syringe (17). The duration for low pressure was 3 min, which was controlled by the screw clamp (15). After 10 min, the T-cock valve (16) was turned to the position that low pressure system was open to atmosphere and the plunger (21) of syringe (17) was pushed to exhaust the air in syringe (17). Then the operation process was repeated.

v) Withdrawal of sampling tube: after extraction, the connection of fluid supply system and low pressure system was taken apart and the sampling tube was taken away from soil. The soil particles stuck to the sampling tube were washed with deionized water.

vi) Elution: the sampling tube was placed in 0.5 mol L^{-1} HCl solution in the elution cylinder (7) for 2 h to elute the nutrient ions absorbed on IEM (2) into elution solution.

vii) Nutrient analysis: when the elution was completed, the sampling tube was taken away. Nutrients in the elution solution were used for P and K measurement. Meanwhile, the sampling tube was soaked in 0.5 mol L^{-1} $NaHCO_3$ solution for next use.

Extraction experiment of DSSNEPU

The whole soil extraction process was performed in a homoeothermic incubator. Each plastic pot contained 1.5 kg of air-dried soil. The pots and the fluid supply system were placed into the homoeothermic incubator that was set at specified temperature for 30 min in advance. Then the sampling tubes were buried into soils for 2 h. The fluid supply system was connected to the sampling tube. The flux speed of deionized water was 1 mL min^{-1}. After treatment, the sampling tubes were taken out. The soil attached to the sampling tubes was rinsed with deionized water. The sampling tubes were eluted with 0.5 mol L^{-1} HCl for 2 h. The concentrations of P and K in elution solution were determined.

To study the effect of burial duration on P and K extraction, 4 burial durations were set as 1, 2, 4 and 24 h. The soil temperature was set at 20 °C in this experiment. To study the effect of soil temperature on nutrient extraction, 4 temperature treatments were set as 10, 20, 30 and 40 °C. To study the effect of low pressure on nutrient extraction, 2 pressure treatments were set as 0 and −50 kPa. The plunger of the syringe in low pressure system was pulled to the set position according to the theoretical calculation (the ideal gas equation) to produce the low pressure of −50 kPa.

Chemical extraction experiment

To study the correlation between the nutrients extracted by DSSNEPU and available nutrients measured by chemical extraction technique, the chemical extraction of soil available nutrient was conducted. The soil sample was shaken with 0.03 mol L^{-1} HF-0.025 mol L^{-1} HCl mixed solution and 1 mol L^{-1} NH_4OAc (pH 7) solution to extract available P and K, respectively (Bao, 1999; Tan, 2005). The extraction time was 30 min. The temperature for extraction was 25 °C. Extraction solution was filtered before measurement. Three sample replicates were tested for each treatment soil.

P and K absorbed by plant roots

To correlate the nutrients extracted by DSSNEPU with those absorbed by plant roots, plant nutrient uptake was evaluated in a number of plant species, including soybean (*Glycine max* (L.) Merr. cv. Brazil 10), water spinach (*Ipomoea quatica* Forssk. cv Baiguliuye), tomato (*Lycopersicon esculentum* (L.) Mill. cv CL035) and rape (*Brassica rapa* var. *oleifera* D.C.). Briefly, plant seeds of similar size were sterilized with 10% NaClO (sodium hypochlorite) for 10 min, rinsed thoroughly with deionized water, and germinated on moist filter paper for 3 d in an incubator at 25 °C. After germination, the seedlings of the similar size were cultivated in quartz sand. At 2-euphylla stage, the seedlings were transplanted into the soils in plastic pots. Each pot contained one plant. Eight replicates were set for each treatment. The experiment were conducted in the greenhouse of the College of Natural Resources and Environment, South China Agricultural University, where daily photoperiod was 10 h and the maximum temperature was 35 °C during this experiment. The average temperature was 30 °C at daytime and 25 °C at night. The relative humidity was between 50%–70%. The pots were arranged as a completely randomized design. Each plant was watered once a day to keep soil moisture at 80% of field water-holding capacity. No additional fertilizer was added during the experiment. After 38-d growth (July 12 to August 19), plant seedlings were harvested and weighed. A 0.5 g ground plant sample from each replicate was digested with H_2SO_4-H_2O_2 using a temperature-controlled digestion block for P and K measurement (Bao, 1999).

Measurement and statistical analyses

The concentrations of P and K in elution solution, soil extraction and plant digest solution were determined by the molybdenum-antimony-ascorbic acid blue photometric method (for P) and the flame photometric method (for K). Blank samples were set in every test. Please see Bao (1999) for the details.

The means and standard errors of all data were calculated by the software of Microsoft Excel 2007. Analysis of variance (ANOVA) with Tukey's multiple range tests at the confidence interval of 95% and correlation analysis of linear regression were done in the SAS system for Windows 9.0.

RESULTS

Construction of DSSNEPU

The DSSNEPU consists of a sampling tube, a fluid supply system, a low pressure system, a tube sheath and an elution cylinder (Fig. 2). The upper end of the sampling tube connects with a fluid supply system and a low pressure system.

The sampling tube includes a sampling tube frame (1) and a piece of IEM (2) that covers on the surface of tube frame (1). The function of IEM (2) is to absorb nutrient ions from soil. The channels (3, 4) on tube frame deliver deionized water from fluid supply system to the IEM (2). The holes (5) among ring channels (4) transmit the low pressure and promote the translocation of soil nutrient ions toward the sampling tube. The fluid supply system consists of a fluid storage bottle (8), an air pipe (9), a fluid pipe (10), a flux controller (11) and a dropper (12). The function of fluid supply system is to keep the IEM and rhizosphere moist and a good contact between them. The low pressure system is made up of a tube stopper (13), a vent pipe (14), a screw clamp (15), a T-cock valve (16) and a syringe (17). The screw clamp (15) controls the length of pressure equilibrium time. The plunger of syringe (17) can be fixed in the barrel (18) with the notch (20) on the plunger shaft (21) and the slice (22) on the barrel (18). The function of low pressure system is to generate the pressure lower than atmosphere in inner space of sampling tube, which would promote the

translocation of soil nutrient ions toward the sampling tube. Using the DSSNEPU, we performed a series of experiments to extract P and K under different treatments.

Effect of burial duration on extracted P and K

According to the designed parameters and operation protocols of the device, we examined the effect of burial duration on P and K that were extracted with DSSNEPU. Both P and K extracted by DSSNEPU increased with the increasing extraction durations (Table I). For extracted P, its value reached a plateau stage after 4 h extraction. A similar tendency of extracted P from soil was observed in the soils of different fertilities. The extracted K value became stable after 2 h extraction. In comparison to those of 1 h extraction, the values of P extracted by DSSNEPU for 2 h were increased by 38.6%, 132% and 52.6% in low, medium and high fertility soils, respectively. The corresponding values for K extraction were increased by 1.85 to 7.20 times.

Effect of soil temperature on extracted P and K

Apart from the impact of burial duration, we also examined the effect of temperature on extracted P and K. The results indicated that extracted P and K tended to increase with increasing temperatures (Table II). Extracted P and K reached the maximal value at the temperature between 30 and 40 °C. Extracted P and K at 10 °C were significantly lower than those over 10 °C. Schoenau *et al.* (1993) suggested that extracted nutrients with IEM were sensitive to temperatures less than 10 °C. Our results supported Schoenau's view. According to the multiple comparisons among different treatments, extracted P did not differ between 30 and 40 °C in low fertility soils while all results didn't differ in all temperatures in high fertility. The temperature for maximized P extraction decreased with elevating soil fertilities (Table II). Extracted P in low, medium and high fertility soils at 40 °C was increased by 75.0%, 27.3% and 18.8%, respectively, compared with those at 10 °C. Effect of temperature on extracted K was larger than that on extracted P especially in medium and high fertility soils (Table II). The corresponding values of extracted K at 40 °C were 0.78, 2.14 and 1.62 times those at 10 °C.

Effect of low pressure system on extracted P and K

As an innovative component, a low pressure system

TABLE I

P and K extracted by the Device for Simulating Soil Nutrient Extraction and Plant Uptake at different extraction durations

Time	Low fertility		Medium fertility		High fertility	
	P	K	P	K	P	K
h	μg cm^{-2}					
1	0.057±0.006[a)]c[b)]	1.28±0.26c	0.072±0.001b	2.24±0.09b	0.135±0.015b	5.44±0.01b
2	0.079±0.005b	3.65±0.20b	0.167±0.016a	18.37±0.09a	0.206±0.034b	29.74±0.80a
4	0.113±0.003a	4.36±0.14ab	0.153±0.012a	18.57±2.63a	0.316±0.028a	29.35±1.84a
24	0.123±0.004a	5.01±0.21a	0.128±0.009a	15.87±0.64a	0.403±0.001a	26.11±0.30a

[a)] Means±standard errors ($n = 3$).
[b)] Means followed by the same letters within each column are not significantly different at $P < 0.05$ using Tukey's multiple comparison test.

TABLE II

P and K extracted by the Device for Simulating Soil Nutrient Extraction and Plant Uptake at different temperatures

Temperature	Low fertility		Medium fertility		High fertility	
	P	K	P	K	P	K
°C	μg cm^{-2}					
10	0.04±0.01[a)]b[b)]	2.41±0.16a	0.11±0.01b	3.85±0.23c	0.16±0.01a	6.23±0.99b
20	0.05±0.01b	2.09±0.03a	0.12±0.01ab	4.77±0.55bc	0.18±0.01a	7.78±0.04ab
30	0.05±0.01b	1.98±0.23a	0.13±0.01a	6.29±0.17ab	0.19±0.02a	9.36±0.35a
40	0.07±0.01a	1.89±0.10a	0.14±0.01a	8.25±0.58a	0.19±0.02a	10.14±0.35a

[a)] Means±standard errors ($n = 3$).
[b)] Means followed by the same letters within each column are not significantly different at $P < 0.05$ using Tukey's multiple comparison test.

plays an important role in enhancing extraction efficiency of nutrients with our device (Fig. 2). The results from Table III indicated that P extracted by DSSNEPU with employing low pressure system was increased by 36.8% to 180% in comparison to those without low pressure system. The corresponding value for K was increased in the range from 53.9% to 115%. The promoting effect of low pressure system on extracted P decreased with increasing concentrations of available P in soil. On the contrary, the promoting effect of low pressure system on extracted K increased with increasing concentrations of available K in soil (Table III).

Correlations between P and K extracted by DSSNEPU and conventional chemical extraction

The results from Table IV indicated that extracted P by two methods increased with increasing soil fertilities. A similar tendency was also observed in K extraction from two methods. The linear regression equations and coefficients determined for the relationships between P and K extracted by DSSNEPU and those by chemical method were: $Y_P = 0.00395X_P + 0.14406$ ($r^2 = 0.9678^{**}$, $n = 9$); $Y_K = 0.10029X_K - 0.38869$ ($r^2 = 0.9633^{**}$, $n = 9$), where Y is the value of DSSNEPU (μg cm^{-2}), X is the value of conventional chemical extraction (mg kg^{-1}). According to the equations of linear regression, P and K extracted by DSSNEPU were correlated with those by the conventional chemical extraction method. It was suggested that the results obtained by DSSNEPU could be converted to those by conventional chemical extraction for the sake of making the comparison with previous data obtained from conventional chemical extraction.

Correlations between P and K extracted by DSSNEPU and absorbed by plants

To assess the reliability of the results obtained by DSSNEPU, we also compared the results obtained by DSSNEPU with those absorbed by plants. The results from Table V indicated that soybean, tomato, water spinach and rape responded differently to increasing soil fertilities. For water spinach, the biomass increased significantly with increasing soil fertilities. For soybean, tomato, and rape, no difference in biomass was observed between medium and high fertility soils. Noteworthy, P and K absorbed by plants increased with elevated soil fertility. However, four plants responded differently to soil fertility due to their different properties in nutrient utilization. The results suggested

TABLE III

P and K extracted by the Device for Simulating Soil Nutrient Extraction and Plant Uptake with or without employing low pressure system

Treatment	P		K	
	No employing low pressure system	Employing low pressure system	No employing low pressure system	Employing low pressure system
	μg cm^{-2}			
Low fertility	0.05±0.01[a)]b[b)]	0.14±0.01a	1.98±0.23b	3.66±0.02a
Medium fertility	0.13±0.01b	0.19±0.01a	6.29±0.17b	9.68±0.44a
High fertility	0.19±0.02b	0.26±0.03a	9.36±0.35b	20.16±0.11a

[a)] Means±standard errors ($n = 3$).
[b)] Means followed by the same letters within each row are not significantly different at $P < 0.05$ using Tukey's multiple comparison test.

TABLE IV

P and K extracted by the Device for Simulating Soil Nutrient Extraction and Plant Uptake (DSSNEPU) and the chemical extraction method

Treatment	P extracted by		K extracted by	
	Chemical extraction	DSSNEPU	Chemical extraction	DSSNEPU
	mg kg^{-1}	μg cm^{-2}	mg kg^{-1}	μg cm^{-2}
Low fertility	0.65±0.01[a)]c[b)]	0.14±0.01c	67.0±1.3c	3.66±0.02c
Medium fertility	3.61±0.10b	0.19±0.01b	152.9±3.3b	9.68±0.44b
High fertility	7.95±0.35a	0.26±0.03a	230.1±2.3a	20.16±0.11a

[a)] Means±standard errors ($n = 3$).
[b)] Means followed by the same letters within each column are not significantly different at $P < 0.05$ using Tukey's multiple comparison test.

TABLE V

Dry weight, P and K uptake of plants growing under three levels of soil fertility

Treatment	Soybean	Tomato	Water spinach	Rape
		Dry weight (g plant^{-1})		
Low fertility	0.89±0.11[a)]b[b)]	0.052±0.007c	0.32±0.03c	0.15±0.01b
Medium fertility	2.36±0.18a	0.43±0.02b	1.09±0.09b	0.91±0.12a
High fertility	2.41±0.30a	0.50±0.02a	1.43±0.09a	1.05±0.08a
		K uptake (mg g^{-1})		
Low fertility	19.04±1.48b	37.51±2.32b	28.23±1.60a	27.67±0.50b
Medium fertility	22.43±0.80b	41.60±0.99b	25.30±2.32a	42.23±0.79a
High fertility	27.55±1.36a	50.54±2.00a	31.07±2.43a	48.38±1.32a
		P uptake (mg g^{-1})		
Low fertility	1.00±0.12c	1.58±0.22b	0.21±0.07c	1.60±0.05c
Medium fertility	1.87±0.09b	1.67±0.07b	1.58±0.14b	4.20±0.16b
High fertility	2.32±0.14a	2.32±0.08a	2.10±0.13a	5.49±0.39a

[a)]Means±standard errors ($n = 8$).
[b)]Means followed by the same letters within each column for each parameter are not significantly different at $P < 0.05$ using Tukey's multiple comparison test.

that the biomass, P or K uptake of a single species of plant are not a suitable reference for fertility assessment.

Correlation analysis (Table VI) indicated that both of the results from DSSNEPU and conventional chemical extraction were significantly correlated with those absorbed by plants except K in water spinach. Moreover, the r values between DSSNEPU and plant uptake were higher than those between conventional chemical extraction and plant uptake except for P in tomato and K in rape. The results suggested that DSSNEPU was a good tool to assess soil available nutrients. The results were similar to those reported by previous researches (Qian *et al.*, 1992; Shen *et al.*, 1996; Chen *et al.*, 2007).

DISCUSSION

Device construction

Compared with the previous root simulating devices (Skogley *et al.*, 1990; Schoenau *et al.*, 1993), the fluid supply system and the low pressure system are two improvements of the device in this study (Figs. 1 and 2). The fluid supply system is used to make the deionized water distributed in IEM uniformly, which will keep the soil and ion-exchange membrane (IEM)

TABLE VI

The regression equations and the correlation coefficients (r) among P and K extracted by chemical extraction method (Z_P and Z_K, mg kg^{-1}), the Device for Simulating Soil Nutrient Extraction and Plant Uptake (DSSNEPU) (X_P and X_K, μg cm^{-2}) and plant uptake (Y_P and Y_K, mg g^{-1})

Plant	Method	Equation	$n^{a)}$	r^2
Soybean	Chemical extraction	$Y_P = 0.1693Z_P + 1.0160$	22	0.7093**
		$Y_K = 0.0516Z_K + 15.2392$	23	0.5239**
	DSSNEPU	$Y_P = 11.0968X_P - 0.4302$	22	0.7366**
		$Y_K = 0.5135X_K + 17.2741$	23	0.5353**
Tomato	Chemical extraction	$Y_P = 0.1152Z_P + 1.3345$	16	0.7119**
		$Y_K = 0.0899Z_K + 29.1028$	17	0.5999**
	DSSNEPU	$Y_P = 7.5343X_P + 0.3443$	16	0.6819**
		$Y_K = 0.8211X_K + 33.8873$	17	0.6408**
Water spinach	Chemical extraction	$Y_P = 0.1404Z_P + 0.9838$	23	0.6468**
		$Y_K = 0.0151Z_K + 25.8539$	23	0.0280
	DSSNEPU	$Y_P = 9.1119X_P - 0.2002$	23	0.6584**
		$Y_K = 0.2059X_K + 25.8540$	23	0.0530
Rape	Chemical extraction	$Y_P = 0.4676Z_P + 1.8190$	16	0.7632**
		$Y_K = 0.1286Z_K + 20.5038$	15	0.7507**
	DSSNEPU	$Y_P = 31.0687X_P - 2.2696$	16	0.7932**
		$Y_K = 1.1597X_K + 27.1236$	15	0.6608**

**Significant at $P \leq 0.01$ level.
[a)]Since some suspicious samples were excluded, the number of sample replicates was less than 24.

moist at a stable level and a good contact between soil and IEM. Factors such as field capacity, the initial soil water content and the permeation speed of soil solution or deionized water through IEM should be considered in the determination of the deionized water supply flux. Considering the dropper is easily blocked up by soil particle and water permeability of IEM is relatively low, the dropper is inserted into the slit between sampling tube frame and IEM to make proper moist effect.

Interception, mass flow and diffusion are three main pathways of soil nutrient movement toward roots (Mengel *et al.*, 2001). However, the previous IEM-based devices lacked the equipment to supply water and to simulate root pressure. As a result, mass flow almost did not occur in the rhizosphere and the diffusion was weak in soil while applying those devices. Thus the previous devices of plant root simulation could not completely imitate the process and result of plant root nutrient uptake. Apart from the concern that losing adequate contact with soil when the soil was dry or heavy texture, PRS^{TM} was also weaker than plant roots in the nutrient absorption competition when PRS^{TM} was buried near plants (Sulewski *et al.*, 2002). Therefore our device with low pressure system and fluid supply system is able to overcome the shortcomings of the previous devices. The low pressure system of the device could make soil and sampling tube contact tightly. The low pressure in the inner space of sampling tube could attract the soil solution in rhizosphere space, and imitate mass flow formation. The IEM intercepts the ions from the soil particle and those dissolved in soil solution, which simulates diffusion and interception process in rhizosphere. When the concentration gradient of nutrients forms in the rhizosphere, diffusion process occurs subsequently in wider soil zone. Our results indicated that a syringe of 50 mL was suitable for low pressure system because most of portable soil solution samplers were equipped with a 50 mL syringe as the sampling tool and it performed optimally in common occasions. Therefore the low pressure generated by a 50 mL syringe (−50 kPa) was used in our device when the plunger was pulled to the position of 50 mL. A vacuum pump is a better choice to connect with our device if the steady pressure is required.

Procedures for using DSSNEPU

The main operation protocols for DSSNEPU were similar to those of the previous IEM-based devices (Schoenau *et al.*, 1993; Hangs *et al.*, 2002), except the pretreatment of sampling tube before burial. According to our experiment, $NaHCO_3$ solution should be changed at least twice and the total soaking time should be over 24 h, which would make the IEM to absorb adequate Na^+ or HCO_3^- for rear extraction. In addition, the IEM should be rinsed thoroughly with deionized water to remove the residual $NaHCO_3$ before burial, since the liquid membrane of $NaHCO_3$ adhered to IEM will hinder the exchange of ions between IEM, soil particle and soil solution. Therefore, it is necessary to soak the sampling tube in deionized water for over 24 h after rinsing with deionized water in order to ensure the rinsing effect.

The burial duration of IEM in the previous studies varied according to different experiment objectives, ranging from 15 min to 2 weeks (Qian *et al.*, 1992; Li *et al.*, 2001). Our results suggested that 4-h extraction was a suitable time for both P and K extraction with DSSNEPU, which was probably attributed to the application of the fluid supply system and the low pressure system. The results from DSSNEPU were highly correlated with those by chemical extraction and plant uptake (Table VI). The kinetic property of our device in temperature was similar to previous devices (Schoenau *et al.*, 1993). Taken together, the results suggest that this device is applicable to assess the availability of P and K in soils.

Application of DSSNEPU

The application of DSSNEPU is not limited in soil science and plant nutrition, environmental science, ecology and other disciplines concerning soil are also the stage of DSSNEPU. However, as a novel device, there are still some disadvantages in DSSNEPU. For instance, due to the high affinity with IEM, Al^{3+} and Fe^{3+} in soil solution would interfere with the extraction of monovalent and bivalent elements (He and Huang, 1995) and lower the results of extraction. Higher concentrations of $NaHCO_3$ and HCl solution should be used in pretreatment and elution process, which would guarantee a complete desorption of ions from IEM to solution, thus ensure the accuracy of later experiments. Noteworthy, we suggest that 0.15–0.30 μg P cm^{-2} and 5–10 μg K cm^{-2} can be regarded as the critical values of soil available P and soil readily available K according to our experiments and the previous criteria of soil nutrient status based on chemical extraction. If the result of available P measured by DSSNEPU is over 0.3 μg cm^{-2} or available K over 10 μg cm^{-2}, the soil can be regarded as fertile soils. However the criteria is just a preliminary result, more laboratory, pot and field experiments are needed to establish the accurate criteria of soil nutrient status by using DSSNEPU as compared

with conventional chemical extraction method in near future.

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