

## Impacts of Chicken Manure and Irrigation on Base Cation Input-Output Budgets in a Vegetable Production System

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**Abstract:** Base cations input-output budgets are usually considered as important indicators for the sustainability of agricultural production systems. In vegetable production systems, excessive inputs of manure and irrigation water may disturb the base cations budgets. A case study on the base cation input-output budgets of greenhouse was carried out in Shouguang, a typical greenhouse vegetable production region in Northern China. From Feb, 2009 to Jan, 2010, researchers evaluated base cation input-output budgets and identified the most important input and output pathways of base cations under three urea management levels. The balances of base cations showed net surpluses of 5.2-34.1 kmol 1/2 Ca<sup>2+</sup>, 25.2-30.0 kmol 1/2 Mg<sup>2+</sup>, 12.0-15.9 kmol K<sup>+</sup> and 22.1-25.1 kmol Na<sup>+</sup>/ha/year under different Nitrogen (N) levels. Different N levels did not produce significantly different effects on the budgets of base cations. The major contributor to Ca<sup>2+</sup>, Mg<sup>2+</sup> and Na<sup>+</sup> surpluses was irrigation water whereas the main contributor to K<sup>+</sup> surplus was the overuse of potassium (K) fertilizer. Chicken manure also was an important contributor to Ca<sup>2+</sup>, Mg<sup>2+</sup> and K<sup>+</sup> surpluses but not to Na<sup>+</sup> surplus. The surpluses have changed the composition of soil exchangeable base cations and pose a potential threat to soil quality and crop growth. Furthermore, surplus K in soil can be lost through leaching which is a waste of resources.

**Key words:** Base cation budgets, chicken manure, irrigation water, input and output pathways, surplus, China

### INTRODUCTION

Due to the high market and nutritional values of vegetables, the area devoted to vegetable crops is increasing yearly in China. Specifically, the greenhouse vegetable area has reached 3.3 million ha (Zhang *et al.*, 2010). Compared with other croplands, vegetable fields are usually treated with larger inputs of nutrients and irrigation water. For instance in Shouguang, one of the most famous vegetable production areas in China, total application rates of air-dried chicken manure on greenhouse vegetables have been >20 ton/ha/year (He *et al.*, 2009). The local irrigation input is commonly as high as 1300 mm year<sup>-1</sup> as well (Zhu *et al.*, 2005).

The excessive inputs will inevitably disturb the nutrient balance of the ecosystem and may lead to rapid accumulation of nutrients, salinity of soil, groundwater contamination etc. (Chen *et al.*, 2004; Shi *et al.*, 2009). In the past few years, many researchers have been committed to evaluating nutrient balance of N and P, especially for N in greenhouse vegetable systems and establishing adequate recommendation system for N application to attain high yield while to alleviate the risk

of environmental pollution (He *et al.*, 2007; Ren *et al.*, 2010). However in fact, only assessing N, P balance and optimizing N, P management was far from adequate. If the N, P management is appropriate but other nutrients management is very improper then the production system is still not sustainable. So, it is very necessary to study the budgets of other nutrients in intensive vegetable cropping system.

To make the research more efficient, researchers chose base cations to study. In general, base cations including calcium (Ca<sup>2+</sup>), magnesium (Mg<sup>2+</sup>), potassium (K<sup>+</sup>) and sodium (Na<sup>+</sup>) are typically absorbed to soil particles and can be taken up by plant roots for use as nutrients important for plant growth (Brady and Weil, 1996; Lovblad *et al.*, 2004). Furthermore, they are closely correlated with the chemical properties, condition and quality of soil such as CEC, moisture and soil salinity. If some of them are removed seriously from soil, plant growth will be affected (Dahlgren and Singer, 1991). In contrast if one or some of them, particularly Na<sup>+</sup> is or are accumulated in soil, it or they can interfere with the uptake of other nutrients by plants and even destroy soil structure and impede plant growth (Cramer *et al.*, 1987;

Dantas *et al.*, 2007). Therefore, it is very valuable to evaluate base cation input-output budgets in intensive vegetable cropping system which is closely related to the sustainability of vegetable production. So far, data on base cation input-output budgets in greenhouse vegetable cropping systems are lacking. The objectives of this study were:

- To estimate the effects of chicken manure and irrigation on  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^{+}$  and  $\text{Na}^{+}$  input-output budgets under different N managements
- To identify the most important input and output pathways of base cations as well as to assess the distribution of base cations in plants
- To evaluate the potential impacts of current nutrient management on soil quality and plant growth and to develop suggestions for further nutrient management

## MATERIALS AND METHODS

**Experimental site:** The study was conducted at Luojia village ( $36^{\circ}55'\text{N}$ ,  $118^{\circ}45'\text{E}$ ), Shouguang county, Shandong province. The elected greenhouse ( $84 \times 8.5 \text{ m}$ ) in this study has a 10 years cropping history of continuous tomato production with two crops per year. The average soil pH ( $0.01\text{M CaCl}_2$ ) values under different treatments were 7.3 and 7.4, CEC 18.5 and 17.1  $\text{cmol kg}^{-1}$  at 0-30 and 30-60 cm depth, respectively in January, 2010. About 0-30 cm soil layers had 460 g sand  $\text{kg}^{-1}$ , 520 g silt  $\text{kg}^{-1}$  and 20 g clay  $\text{kg}^{-1}$ ; 30-60 cm layers had 370 g sand  $\text{kg}^{-1}$ , 600 g silt  $\text{kg}^{-1}$  and 30 g clay  $\text{kg}^{-1}$  (Ren *et al.*, 2010).

**Crop management and field treatment:** For this study, the entire observation period of base cation budgets started from 16 February, 2009 to 26 January, 2010, covering two tomato-growing seasons and a Summer fallow duration. Before transplanting tomato seedlings (*Lycopersicon esculentum* Mill., a vegetable of broad adaptation in the region), the fields were thoroughly tilled with air-dried chicken manure and chemical fertilizer P, K. In each season, all plots received 150 kg  $\text{P}_2\text{O}_5 \text{ ha}^{-1}$  as calcium superphosphate (12%  $\text{P}_2\text{O}_5$ ; 28% CaO) and 520 kg  $\text{K}_2\text{O ha}^{-1}$  as potassium sulfate (50%  $\text{K}_2\text{O}$ ). Chemical N fertilizer (urea) was applied with irrigation according to the different crop-growth stages. Irrigation water was applied at the rates of 50 mm each time with a total annual input of 1105 mm. Three treatments with three replications were carried out in a randomized block design; CK: Neither organic manure nor chemical fertilizer N was used.

**Conventional N management (CN):** Air-dried chicken manure was broadcasted as a basal fertilizer. The

application rates were 10 and 8 ton  $\text{ha}^{-1}$  in two growing seasons, supplying 270 and 190 kg N  $\text{ha}^{-1}$ , respectively. N fertilizer was side-dressed following the local conventional fertilization practices with an N side dressing rate of 120 kg N  $\text{ha}^{-1}$  on each occasion (10 times  $\text{year}^{-1}$ ); recommended N management (RN): Chicken manure was applied at the same rate as that in the CN treatment and N side-dressing of rate of 50 kg N  $\text{ha}^{-1}$  was added before fruit cluster development (8 times  $\text{year}^{-1}$ ). Each plot size was  $7.8 \times 5.6 \text{ m}$ .

**Equipment installation and water sampling:** In each plot, a microporous ceramic suction cup was installed at 90 cm soil depth. Soil solution was extracted continuously using the suction cups every 10 days (for technical details on seepage-water collection (Mack *et al.*, 2005). The soil solution samples were taken into plastic bottles, transported to the laboratory and stored at  $-20^{\circ}\text{C}$  until analyzed. To monitor matrix potential, two tensiometers were installed at 80 and 100 cm soil depth around each suction cup with a horizontal distance of 10 cm. They were monitored every 2 days.

**Calculation for leached amount of base cations:** The amount of base cations leached at the depth of 90 cm was obtained from the equation:

$$N = \sum c_i \Delta Q_i \quad (1)$$

where  $c_i$  is the ion concentration either  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^{+}$  or  $\text{K}^{+}$  in the soil solution samples; the drainage component  $Q$  at 90 cm depth was calculated based on the following equation:

$$Q = \sum j_i \Delta t_i \quad (2)$$

where  $\Delta t_i$ , the time of period (d);  $j$  ( $\text{cm d}^{-1}$ ) is volumetric flux density calculated by Darcy's law:

$$J_w = K \frac{\Delta H}{\Delta Z} \quad (3)$$

The hydraulic conductivity  $K$  was estimated with the Van Genuchten (1980):

$$K = K_s \frac{\left\{ 1 - (\alpha |\phi|)^{n-1} \left[ 1 + (\alpha |\phi|)^n \right]^{-m} \right\}^2}{\left[ 1 + (\alpha |\phi|)^n \right]^{m/2}} \quad (4)$$

Where:

$K_s$  = The hydraulic conductivity at saturation ( $K_s = 4.43 \text{ cm day}^{-1}$ )

m, n and  $\alpha$  = Parameters derived from the soil moisture-characteristic ( $\alpha = 46.98$ ,  $n = 1.204$ ,  $m = 0.196$ )

$\varphi$  = The matric potential (cm H<sub>2</sub>O) obtained by tensiometers

**Sampling and analysis:** Soil samples were collected at 0-30 cm soil depth in early December, 2006 and the end of January, 2010. Soil exchangeable Ca, Mg, K and Na were extracted using 0.1 M BaCl<sub>2</sub> (Hendershot *et al.*, 2006). Base cations in soil and soil solution were analyzed by Inductively Coupled Plasma-optical Emission Spectrometry (ICP-OES, Optima3300DV, Perkin-Elmer, Waltham, Mass., USA). Tomato fruits were picked up at each harvest event and the leaves of tomato were collected in crop growing seasons from all plots. The roots and stems were taken at the end of harvesting. Plants samples were divided into fruits, leaves, roots and stems and weighed before and after drying at 70°C for 48 h. Finally, plant samples and air-dried chicken manure were dry ashed at 500°C for 6 h in a furnace and extracted using 10% HCl in order to determinate the contents of Ca, Mg, K and Na (Jones Jr. and Case, 1990; Agbede *et al.*, 2008).

**Statistical analysis:** Data analysis such as analysis of variance and the Least Significant Difference (LSD) at the 0.05 level were performed by SPSS 11.5 software. Results were expressed as means±SD (Standard Deviation).

## RESULTS

**Uptake and removal of base cations by the different parts of tomato plants:** As shown in Table 1, there were considerable differences in amounts of absorption and removal of base cations of different parts of plants. Leaves absorbed the maximum amounts of Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup>. In the base cations absorbed by leaves, the amounts of Ca<sup>2+</sup> were the highest ranging from 19.07-23.54 kmol/ha/year. Roots absorbed and removed the least amounts of Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> which may be because roots cannot be removed completely out of the soil after the harvest, besides their own needs for base cations were not high. The amounts of Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> absorbed by stems were higher than those by fruits with the exception that fruits absorbed more K<sup>+</sup>.

**Soil Ca<sup>2+</sup> input-output budget:** According to Fig. 1, the total input of Ca<sup>2+</sup> via irrigation water was the highest (35.4 kmol/ha/year) followed by the input from chicken manure and fertilizer P. It should be noted that input of Ca<sup>2+</sup> from chicken manure was especially high

Table 1: The uptake and removal of base cations by the different parts of tomato plants under different N treatments

Base cations	Treatments <sup>a</sup>	Roots	Stems	Leaves	Fruits
-----kmol/ha/year <sup>b</sup> -----					
1/2 Ca <sup>2+</sup>	CK	0.36±0.02	1.43±0.15	19.07±3.46	0.69±0.03
	RN	0.28±0.14	1.70±0.16	23.54±3.78	0.73±0.01
	CN	0.29±0.13	1.53±0.15	21.27±1.38	0.78±0.05
1/2Mg <sup>2+</sup>	CK	0.13±0.01	0.74±0.08	7.89±1.43	0.64±0.04
	RN	0.10±0.05	0.88±0.08	9.74±1.98	0.67±0.02
	CN	0.10±0.05	0.79±0.08	8.80±0.56	0.71±0.05
K <sup>+</sup>	CK	0.34±0.02	1.40±0.15	6.74±1.22	5.61±0.23
	RN	0.27±0.13	1.66±0.14	8.32±1.60	5.88±0.09
	CN	0.28±0.11	1.49±0.10	7.52±0.48	6.27±0.42
Na <sup>+</sup>	SS	0.09±0.01	0.41±0.04	1.05±0.12	0.25±0.01
	RN	0.07±0.03	0.49±0.04	1.29±0.25	0.27±0.01
	CN	0.07±0.01	0.44±0.04	1.17±0.07	0.28±0.01

<sup>a</sup>CK, RN and CN represent no N treatment, recommended N management and conventional N management, respectively, <sup>b</sup>Data are means±SD

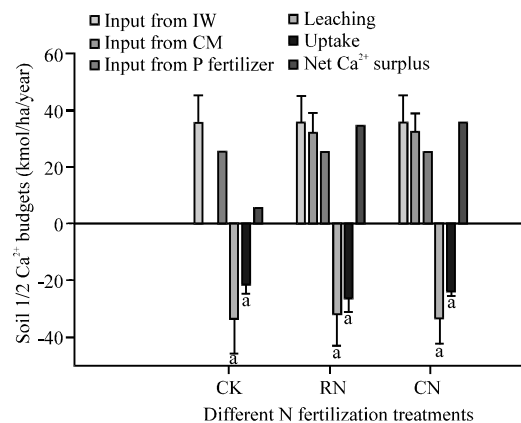


Fig. 1: Soil Ca<sup>2+</sup> input-output budget under different N treatments. IW: Irrigation Water; CM: Chicken Manure. Net Ca<sup>2+</sup> surplus was the amount of net Ca<sup>2+</sup> inputs from irrigation water, manure and P fertilizer minus the amount of loss from plant uptake of Ca<sup>2+</sup> and leaching. CK, RN and CN represent no N treatment, recommended N management and conventional N management, respectively. Means indicated by same letter are not significant different, ANOVA ( $p < 0.05$ ) LSD 0.05

(32.0 kmol/ha/year). The reason is that the calcium mainly comes from the added lime for local farmers usually add lime to chicken manure to remove the unpleasant smell. With regard to outputs of Ca<sup>2+</sup>, the main output pathway was Ca<sup>2+</sup> leaching rather than the uptake and removal of Ca<sup>2+</sup> by plants. The application of different N rates did not have a significant impact on either Ca<sup>2+</sup> leaching or uptake and removal of Ca<sup>2+</sup> by plants. Similarly, the leaching and uptake of Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> were not significant affected by the application of different N rates as well (Fig. 1-4). The net balances of Ca<sup>2+</sup> in the CK, RN and CN treatments

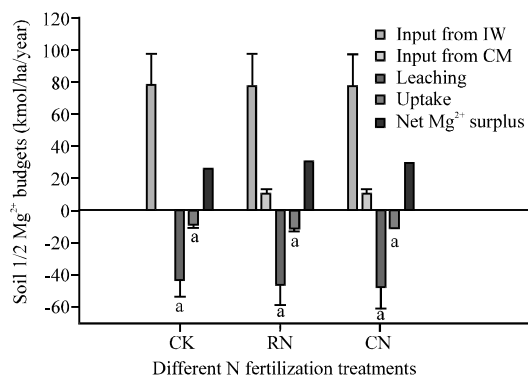


Fig. 2: Soil Mg<sup>2+</sup> input-output budget under different N treatments. IW: Irrigation Water; CM: Chicken Manure. Net Mg<sup>2+</sup> surplus was the amount of net Mg<sup>2+</sup> inputs from irrigation water and manure minus the amount of loss from plant uptake of Mg<sup>2+</sup> and leaching. CK, RN and CN represent no N treatment, recommended N management and conventional N management, respectively. Means indicated by same letter are not significant different, ANOVA ( $p < 0.05$ ) LSD 0.05

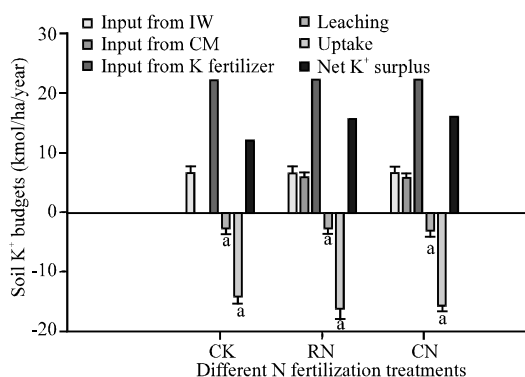


Fig. 3: Soil K<sup>+</sup> input-output budget under different N treatments. IW: Irrigation Water; CM: Chicken Manure. Net K<sup>+</sup> surplus was the amount of net K<sup>+</sup> inputs from irrigation water, manure and K fertilizer minus the amount of loss from plant uptake of K<sup>+</sup> and leaching. CK, RN and CN represent no N treatment, recommended N management and conventional N management respectively. Means indicated by same letter are not significant different, ANOVA ( $p < 0.05$ ) LSD 0.05

were 5.2, 34.1 and 35.4 kmol/ha/year, respectively which indicated net accumulations of Ca<sup>2+</sup> in soil.

**Soil Mg<sup>2+</sup> input-output budget:** Irrigation water was the major contributor to soil Mg<sup>2+</sup> input (Fig. 2). Irrigation water contributed 77.4 kmol Mg<sup>2+</sup>/ha/year which was 7

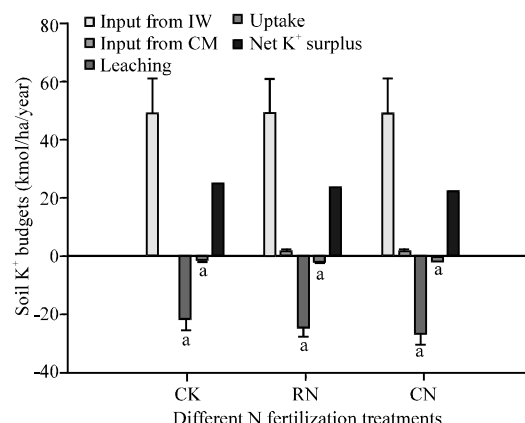


Fig. 4: Soil Na<sup>+</sup> input-output budget under different N treatments. IW: Irrigation Water; CM: Chicken Manure. Net Na<sup>+</sup> surplus was the amount of net Na<sup>+</sup> inputs from irrigation water and manure minus the amount of loss from plant uptake of Na<sup>+</sup> and leaching. CK, RN and CN represent no N treatment, recommended N management and conventional N management, respectively. Means indicated by same letter are not significant different, ANOVA ( $p < 0.05$ ) LSD 0.05

times more than the amount of Mg<sup>2+</sup> supplied by chicken manure. Like Ca<sup>2+</sup>, leaching loss was still the major output pathway under all N treatments (Fig. 2). Compared with leaching losses, the amounts of plants Mg<sup>2+</sup> absorption were little, varying from 9.4-10.4 kmol/ha/year. Overall, the net balances in CK, RN and CN treatment were 25.2, 30.0 and 29.4 kmol/ha/year, respectively.

**Soil K<sup>+</sup> input-output budget:** Unlike Ca<sup>2+</sup> and Mg<sup>2+</sup>, the main K<sup>+</sup> input pathway was application of chemical fertilizer rather than input via irrigation water whereas the main output pathway was plants' absorption rather than leaching loss (Fig. 3).

K<sup>+</sup> input from organic fertilizer was about one fourth that from the chemical fertilizer and slightly less than that from irrigation water.

As expected, tomato plants needed a lot of K<sup>+</sup> to maintain growth. Only depending on inputs from irrigation and organic fertilizer is difficult to meet tomato crop's K needs. But intensified application of K fertilizer can also lead to K accumulation and even leaching. The net budgets of K<sup>+</sup> were as high as 12.0, 15.7 and 15.9 kmol/ha/year in CK, RN and CN treatments, respectively. Moreover, the leaching loss has occurred which ranged from 2.7-3.1 kmol/ha/year in the treatments (Fig. 3).

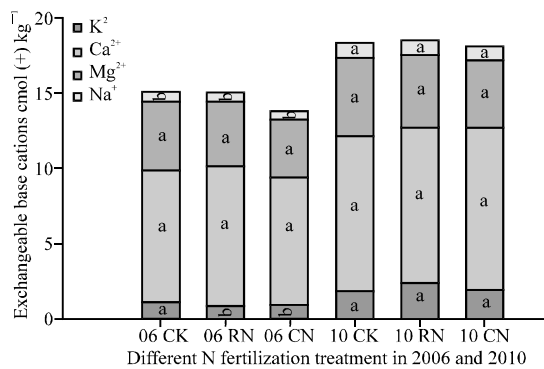


Fig. 5: The alterations of soil exchangeable base cations (0-30 cm) in all N treatments between 2006 and 2010. 06 CK, 06 RN and 06 CN; 10 CK, 10 RN and 10 CN represent no N treatment, recommended N management and conventional N management in 2006 and 2010, respectively. Means indicated by same letter are not significant different, ANOVA ( $p < 0.05$ ) LSD 0.05

**Soil Na<sup>+</sup> input-output budget:** Similar to the Ca<sup>2+</sup> and Mg<sup>2+</sup>, irrigation water is one of the major sources of soil Na<sup>+</sup> (Fig. 4). Compared with irrigation water, the Na<sup>+</sup> input from chicken manure was relatively lower. In addition, leaching was the major output pathway for Na<sup>+</sup>. In contrast, the amounts of Na<sup>+</sup> absorbed and removed by plants were much lower, ranging from 1.8-2.1 kmol/ha/year. The net budgets of Na<sup>+</sup> were 25.1, 23.8 and 22.1 kmol/ha/year in CK, RN and CN treatments, respectively.

**Soil exchangeable base cations:** There were some alterations of soil exchangeable base cations (0-30 cm) between 2006 and 2010. Soil exchangeable Na<sup>+</sup> had increased (by 0.28-0.65) significantly during the period in all treatments. Soil exchangeable K<sup>+</sup> (by 0.95-1.88) also had increased significantly in RN and CN treatments (Fig. 5) whereas the increases of soil exchangeable Mg<sup>2+</sup> and Ca<sup>2+</sup> were not significant.

## DISCUSSION

**N management and soil base cations input-output budget:** N fertilizer application can influence base cations input-output budget to some extent by affecting leaching and uptake of base cations. An adequate supply of N can promote the absorption of base cations through improving biomass production. However, too much N fertilizer application can also cause the accumulation of ammonium which inhibit the uptake of Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> through competition for root absorption sites

(Ruan *et al.*, 2007). But the present study indicated that different N application rates did not produce significantly different effects on the uptake and removal of Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> in plants (Fig. 1-4). Hence results are not in accordance with Sanchez-Chavez *et al.* (2010) who mentioned that with increase of N (NH<sub>4</sub>NO<sub>3</sub>) dose in nutrient solution, the level of Ca<sup>2+</sup>, Mg<sup>2+</sup> and K<sup>+</sup> in roots and leaves of green bean plants firstly rose and then drastically diminished. The reason was probably caused by different forms or rates of N fertilizer or differences between field and laboratory conditions. With regard to leaching of base cations, high concentrations of NH<sub>4</sub><sup>+</sup> which can displace Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> at the soil sites and hence increase the leaching of Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup>. On the other side, NH<sub>4</sub><sup>+</sup> can convert NO<sub>3</sub><sup>-</sup> by the process of nitrification in which H<sup>+</sup> was generated and can also displace exchangeable cations and accelerate leaching losses of cations (Tokuchi *et al.*, 1993). However in the study as N application rates increased, the amount of base cation leached did not significantly increase. These results are in contrast with those of Yanai *et al.* (1998) in which (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> had the potential to increase the leaching of cations. There are two possible explanations for these results. First, as Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> balance showed a lot of surpluses and their content in soil solution was high, the competition ability of NH<sub>4</sub><sup>+</sup> to displace Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup> may be alleviated at the soil sites. Furthermore, under soil pH 7.3-7.4 conditions, H<sup>+</sup> produced by nitrification was consumed quickly and may not be able to displace Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup>.

**Ca<sup>2+</sup>, Mg<sup>2+</sup> budgets and the potential impacts of Ca<sup>2+</sup>, Mg<sup>2+</sup> accumulation on plant growth and soil quality:** Ca<sup>2+</sup> and Mg<sup>2+</sup> play an important role in tomato growth and fruit quality (Caines and Shennan, 1999; Paiva *et al.*, 1998). Throughout the entire growing seasons, tomato plants, especially their leaves require large amounts of Ca<sup>2+</sup> and Mg<sup>2+</sup> (Table 1, Fig. 1 and 2). Thus, it is necessary to maintain certain levels of soil Ca<sup>2+</sup> and Mg<sup>2+</sup> for plant growth. However, if the levels are too high, nutrient uptake will be negatively affected. For one thing, high concentrations of Ca<sup>2+</sup> and Mg<sup>2+</sup> may induce deficiency of K<sup>+</sup> in plants, due to the competition between plant available Mg, Ca and K ions (Marschner, 1995). For another, excess Ca and Mg ions can react with phosphate to produce insoluble P-precipitates (House, 1999) which are less available to the plant. Besides affecting plant nutrient uptake, high levels of Ca<sup>2+</sup> and Mg<sup>2+</sup> in soil also have an impact on some soil properties such as soil salinity.

In the current study, Ca<sup>2+</sup> and Mg<sup>2+</sup> balances in all treatments showed very large surpluses (average 24.9

kmol  $\text{Ca}^{2+}$ /ha/year, 28.2 kmol  $\text{Mg}^{2+}$ /ha/year, Fig. 1 and 2) which have potential impacts on plant nutrient uptake and soil properties. The main contributor to the surpluses of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  was irrigation water (Fig. 1 and 2). Besides, chicken manure and fertilizer P contribute a lot of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  to the surpluses as well (Fig. 1 and 2). In addition, it should be noted the solubility of calcium and magnesium in chicken manure and fertilizer P may be not high. These may weaken the impacts of surplus calcium and magnesium on soil properties and plant growth. Perhaps for this reason from 2006-2010, the increases of soil exchangeable  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  in all treatments were not significant (Fig. 5).

**Soil  $\text{K}^+$  budget and the potential impact of  $\text{K}^+$  accumulation on soil quality and plant growth:** The tomato plant needs a considerable amount of potassium to grow and to produce fruit (Besford, 1975). Actually only fruits can absorb and remove 5.61-6.27 kmol K/ha/year in different treatments which were 5-25 times greater than other cations (Table 1). This indicated that K supply is extremely important for tomato yield. Furthermore, potassium nutrition was studied in relation to the quality of tomato fruit, pest and disease resistance and even plant tolerance to environmental stress (Cakmak, 2005; Amtmann *et al.*, 2008). For example, application of K fertilizer can considerably enhance the adverse effects of salinity to tomatoes under saline stress (Lopez and Satti, 1996). Therefore, maintaining adequate K supply is vital to soil. K is usually thought to be abundant in many soils. But the plant-available K is not high and hardly meets the considerable requirement of plant for potassium (Tisdale *et al.*, 1985). Once the soil has high contents of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , potassium deficiency will become more severe due to the competition among them (Marschner, 1995). Therefore, the addition of K fertilizer is an effective way to improve K supplying ability of the soil. Farmers used to undervalue the effect of K fertilizer, compared with N and P fertilizers. For example, potassium deficiency occurred in half of the surveyed fields of greenhouse-grown tomato from 1996-2000 in Beijing (Chen *et al.*, 2004). However in recent years, farmers have become increasingly aware of the importance of potassium for healthy crop production. For instance, the application rate of K rapidly increased from 972 in 1997-1685 in 2004 kg  $\text{ha}^{-1}$  in Shouguang (Liu *et al.*, 2008). In the present study, at the rate of 1086 kg K/ha/year, there were 12.0-15.9 kmol K/ha/year surpluses. Moreover, the significant increase of soil exchangeable  $\text{K}^+$  in RN and CN treatments also confirmed the result (Fig. 5). It can be speculated that in Shouguang the input of K fertilizer is excessive which can result in K

accumulation in greenhouse soil. A too high K content in soil can depress Mg uptake for K and Mg antagonism (Marschner, 1995). In fact in cucumber cropping systems of the region with a higher rate of K, typical magnesium deficiency symptoms in leaves were visible. This is in line with the report of Romheld and Kirkby (2010). Furthermore, excessive K in soil was lost through leaching which is a waste of resources (Fig. 3). Therefore, future research should focus on optimizing K fertilizer rates and maintaining a sufficient K supply in the soil to match crop K demand, minimize K losses and alleviate its effect on Mg uptake. The soil fertilization combined with foliar feeding may be a good attempt.

**Soil  $\text{Na}^+$  budget and the potential impact of  $\text{Na}^+$  accumulation on soil quality and plant growth:** Na is not considered an essential element for all higher plants with the exception of certain types of  $\text{C}_4$  plants (Subbarao *et al.*, 2002). However, some studies refer to it as a functional nutrient in plant, for it may promote maximal biomass production or replace K in metabolic function (Subbarao *et al.*, 2002). Anyway, the Na demand of tomato crop is less than other cations (Table 1, Fig. 4). In this study, net surpluses of  $\text{Na}^+$  in soil ranged from 22.1-25.1 kmol/ha/year, 10 folds more than the amount of crop  $\text{Na}^+$  demand (Fig. 4). Irrigation water was the major contributor to the net surpluses.

In general most sodium salt is soluble which can leach easily and will not accumulate in soil. However, greenhouse cultivation systems are semi-closed systems covered by polyethylene plastic sheets which basically cannot receive natural rainfall and have no natural leaching process. In the micro-climate, leaching is insufficient and water is removed from soil mainly through soil evaporation and plant transpiration. The soluble salt containing sodium ions in soil water will be left and accumulate in the surface. The accumulation of  $\text{Na}^+$  in soil will affect plant growth. As mentioned above, there are competitive interactions between plant available Mg, Ca and K ions. Likewise, the competitive relationship exists between Mg, Ca, K and Na ions (Cramer *et al.*, 1987; Adams and Ho, 1995). Therefore, the accumulation of  $\text{Na}^+$  will disrupt uptake of Mg, Ca and K ions and may become toxic especially for  $\text{K}^+$  due to similar chemical properties (Marschner, 1995).

Furthermore, the accumulation of Na ions in soil can have a negative effect on some soil properties. In the present study, soil exchangeable  $\text{Na}^+$  in all treatments had increased significantly throughout 4 years (Fig. 5). If Na ions continue to accumulate in soil, soil structure and permeability will be affected and ever destroyed to some extent. This would pose a threat to the sustainability of

vegetable production. To prevent Na problems, it is necessary to peeled off the plastic film of greenhouse during the rainy fallow period in order to get natural rainfall and to promote the soluble salt leaching. In addition, it is also an effective way to greatly increase the amount of irrigation water with low Na only in proper time so as to wash the excess salt out of soil.

## CONCLUSION

In high-input vegetable production systems, all base cation balances showed a lot of surpluses which pose a potential threat to the sustainability of vegetable production. The major contributor to  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{Na}^+$  surpluses was irrigation water whereas the main contributor to  $\text{K}^+$  surplus was the overuse of K fertilizer. The changes of N management levels did not significantly affect the budgets of base cations. Therefore in order to ensure sustainable vegetable production, only depending on effective management of N is far from enough. How to integrate managements of N and other nutrients as well as irrigation management should become one of the key points for future work.

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