Effects of Combined Silicon and Phosphorus Application on Dry Matter Accumulation, Distribution, and Yield of Spring Maize in Low-Phosphorus Soil (Postprint)

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Date: 2017-11-07T00:00:00+00:00

Abstract

Using maize varieties 'Zhenghong 2' and 'Zhenghong 115' as experimental materials, a field plot experiment was conducted in 2014 and 2015 to investigate the effects of combined silicon and phosphorus fertilizer application on net photosynthetic rate, transpiration rate, and leaf area index at the jointing and silking stages, dry matter accumulation and distribution at the jointing, silking, grain-filling, and maturity stages, as well as yield and yield components under low-phosphorus soil conditions, and to explore the yield-increasing effects of silicon application and combined silicon-phosphorus application. The results showed that, compared with the control (no phosphorus or silicon fertilizer application), phosphorus application, silicon application, and combined silicon-phosphorus application treatments all increased leaf area index and net photosynthetic rate at the jointing and silking stages, enhanced dry matter accumulation at each growth stage of jointing, silking, grain-filling, and maturity, decreased the dry matter distribution ratio in leaves at the grain-filling and maturity stages and in stems and sheaths at the grain-filling stage, increased the dry matter distribution ratio in grains and harvest index, reduced barren tip length, increased ear length, and ultimately improved kernels per ear, thousand-grain weight, and grain yield. Among these treatments, the effects of phosphorus application in increasing or decreasing the above indicators were significantly greater than those of silicon application, and the effects of combined silicon-phosphorus application were significantly greater than those of phosphorus or silicon application alone, with silicon and phosphorus exhibiting obvious synergistic and complementary effects. Grain yield in both 2014 and 2015 showed significant positive correlations with dry matter accumulation at the jointing, silking, grain-filling, and maturity stages. Compared with phosphorus application alone, the combined silicon-phosphorus application treatment increased yield by 1,288.57 kg • hm ^{2} (in 2014) and 1,313.61 kg • hm ^{2} (in 2015), with the increase in 2015 being significantly greater than that in 2014, demonstrating a stable yield-increasing effect of silicon and phosphorus. In summary, under low-phosphorus soil conditions in the hilly areas of Sichuan, rational combined application of silicon and phosphorus fertilizers can not only enhance material production capacity and dry matter accumulation during the early growth stage of maize, but also improve dry matter distribution among various maize organs during the late growth stage, promote grain filling and development, and ultimately increase grain yield.

Full Text

Effects of Combined Application of Silicon and Phosphorus Fertilizers on Dry Matter Accumulation, Distribution, and Grain Yield of Spring Maize in Low-Phosphorus Soils

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Abstract

Using maize varieties 'Zhenghong 2' and 'Zhenghong 115' as experimental materials, a two-year field plot experiment (2014–2015) was conducted to investigate the effects of combined silicon and phosphorus fertilizer application on net photosynthetic rate, transpiration rate, and leaf area index at the jointing and silking stages, dry matter accumulation and distribution at the jointing, silking, grain-filling, and maturity stages, and grain yield and yield components in low-phosphorus soils. The synergistic effects of silicon and phosphorus application on yield enhancement were also explored. The results showed that compared with the control (no phosphorus or silicon fertilizer), phosphorus application, silicon application, and combined silicon-phosphorus application all significantly increased leaf area index and net photosynthetic rate at the jointing and silking stages, enhanced dry matter accumulation at all growth stages, reduced dry matter distribution ratios in leaves at the grain-filling and maturity stages and in stems/sheaths at the grain-filling stage, increased dry matter distribution to grains and harvest index, decreased bare tip length, increased ear length, and ultimately improved grains per ear, 1000-kernel weight, and grain yield. The effects of phosphorus fertilizer were markedly greater than those of silicon fertilizer, while combined silicon-phosphorus application showed even stronger effects than either single application, demonstrating clear synergistic and complementary effects. Grain yield in both 2014 and 2015 was significantly positively correlated with dry matter accumulation at the jointing, silking, grain-filling, and maturity stages. Compared with phosphorus application alone, combined silicon-phosphorus application increased grain yield by 1,288.57 kg • hm ^{2} in 2014 and 1,313.61 kg • hm ^{2} in 2015, with the yield increase being more pronounced in 2015. These results indicate that under low-phosphorus soil conditions in the hilly regions of Sichuan, rational combined application of silicon and phosphorus fertilizers can enhance photosynthetic production and dry matter accumulation during early growth stages, optimize dry matter distribution among organs during later stages, promote grain filling, and ultimately increase grain yield.

Keywords: Low phosphorus soil; Maize; Silicon fertilizer; Phosphorus fertilizer; Photosynthesis; Dry matter accumulation; Yield

Introduction

Plants synthesize and accumulate organic matter through photosynthesis, and crop economic yield is determined by both biological yield and harvest index. In current maize (*Zea mays*) production systems where grain is the primary harvest target, grain yield is closely related to dry matter accumulation. Previous studies have shown that dry matter accumulation from silking to maturity accounts for over 60% of total seasonal accumulation in high-yielding maize populations, with grain yield primarily derived from photosynthates produced by leaves during mid-to-late growth stages and from remobilization of stored materials from stems and leaves. The synthesis, accumulation, and distribution of assimilates during mid-to-late grain filling stages exert the greatest influence on economic yield. Various agronomic practices—including increasing plant density, optimizing fertilization, breeding improved varieties, and refining cultivation methods—have been employed to enhance dry matter accumulation, improve photosynthetic capacity, and regulate dry matter distribution to achieve high yields, with fertilization management being the most common and critical approach.

In the hilly regions of Sichuan Province, although soil testing and formula fertilization have increased soil phosphorus content in recent years, phosphorus-deficient soils remain widespread, and substantial phosphorus fertilizer inputs are still required for grain and oil crop production. However, global phosphate rock reserves are limited, and at current application rates, these resources may be depleted within 50 years. Low fertilizer use efficiency in China, with phosphorus use efficiency for major grain crops ranging from only 7% to 20.1%, is attributed to excessive fertilization, neglect of soil nutrient sources and utilization, insufficient exploitation of crop yield potential, and inadequate measures to reduce soil nutrient losses. Maize is a phosphorus-demanding crop that is highly sensitive to phosphorus deficiency. Phosphorus application increases dry matter accumulation in all maize organs, enhances photosynthetic capacity, improves plant uptake of nitrogen, phosphorus, and potassium, and increases grain yield.

Silicon benefits maize growth, with silicon content in various maize organs ranging from 4 to 75 g · kg ^{1}. Positive correlations exist between silicon content and nitrogen, phosphorus, and potassium contents in maize organs. Silicon application improves crop nutrient uptake and utilization, enhances photosynthetic production, increases dry matter accumulation, and boosts yield. Due to their similar chemical properties, silicon and phosphorus may exhibit mutually promoting fertilizer effects. Research suggests silicon can alleviate low-phosphorus stress in maize and improve soil and plant nutrient environments. Moreover, silicon fertilizer reserves are abundant, production technology is maturing, and silicon offers numerous benefits for crop growth, indicating broad prospects for application in sustainable agriculture and emission reduction.

Whether combined silicon-phosphorus application can improve photosynthetic production, increase dry matter accumulation, optimize late-season dry matter distribution, and enhance maize yield in rain-fed low-phosphorus soils of Sichuan' s hilly uplands requires further investigation. This study used maize varieties 'Zhenghong 2' and 'Zhenghong 115' to examine the effects of combined silicon-phosphorus application on dry matter synthesis, accumulation, and distribution characteristics and yield under low-phosphorus soil conditions, aiming to provide a theoretical basis for developing high-yield cultivation techniques integrating nitrogen, phosphorus, potassium, and silicon fertilizers.

1.1 Experimental Design

A two-year field experiment was conducted in 2014 and 2015 at Yingming Village, Lujia Town, Jianyang City, Sichuan Province (30°70 N, 103°86 E). The experimental site is located on a hilly terrace with thin soil layers and rain-fed conditions. The region has a subtropical humid climate with abundant heat resources, an average annual temperature of 16–18°C, active accumulated temperature above 10°C of 5,500–6,000°C, a frost-free period of 280–350 days, and annual rainfall of 900–1,000 mm unevenly distributed, mainly from June to August. Spring sowing was practiced in both years. Temperature and rainfall distributions during the maize growing season (April–July) in 2014 and 2015 are shown in [Figure 1: see original paper].

The experimental soil was brown purple soil developed from purple sandstone mudstone parent material, with pH 7.68±0.15, organic matter content 15.58 g · kg ^{1}, alkali-hydrolyzable nitrogen 34.09 mg · kg ^{1}, available phosphorus 4.92 mg · kg ^{1}, available potassium 124.50 mg · kg ^{1}, and available silicon 210.93 mg · kg ^{1}, classifying it as low-phosphorus and low-silicon soil.

Maize varieties 'Zhenghong 2' and 'Zhenghong 115' were used. In 2014, seedlings were raised on March 28 and transplanted on April 1 at the 2-leaf-1-heart stage using a wide-narrow row planting pattern (wide row 1.6 m, narrow row 0.4 m) with 0.2 m spacing between plants, achieving a density of approximately 50,000 plants · hm ^{2}. Harvest occurred on July 29, 2014. Wheat was sown on

October 25, 2014 without any fertilizer to further deplete soil nutrients. In 2015, wheat plants were removed on March 25, fields were prepared, and maize was direct-seeded on April 3 using the same wide-narrow row pattern. Seedlings were thinned on April 21 to one vigorous plant per hole, maintaining the same density, with harvest on July 26, 2015.

A split-plot design was employed with maize variety as the main plot factor (two varieties: 'Zhenghong 2' and 'Zhenghong 115') and fertilizer combination as the subplot factor (four silicon-phosphorus combinations): P0Si0 (phosphorus 0 kg · hm ^{2}, silicon 0 kg · hm ^{2}), P0Si75 (phosphorus 0 kg · hm ^{2}, silicon 75 kg · hm ^{2}), P60Si0 (phosphorus 60 kg · hm ^{2}, silicon 0 kg · hm ^{2}), and P60Si75 (phosphorus 60 kg · hm ^{2}, silicon 75 kg · hm ^{2}). Phosphorus fertilizer was calcium superphosphate (P O 12%), and silicon fertilizer was Mile soil conditioner (SiO 20%, provided by Shanxi Mile Fertilizer Industry Co., Ltd.). Three replications were established, totaling 24 plots with each plot area of 17 m^2.

The same plot layout and treatments were used in both years. All plots received pure nitrogen (urea, N 46%) at 180 kg · hm ^{2} and K O (potassium chloride, K O 60%) at 90 kg · hm ^{2}. Potassium contributed by silicon fertilizer was deducted from potassium fertilizer application, and calcium and magnesium were supplemented with calcium chloride and magnesium chloride in treatments without silicon fertilizer. All nitrogen, phosphorus, potassium, and silicon fertilizers were applied as basal fertilizers, mixed thoroughly and broadcast on narrow rows, then covered with 5-8 cm of soil and watered to moisten the 0–25 cm soil layer. In 2014, uniform vigorous seedlings were transplanted with soil after ridge formation and mulching on day 3; in 2015, seeds were direct-seeded (2 seeds per hole) on day 2 after ridge formation and mulching. Plastic mulch was removed at the large trumpet stage in both years. Other field management practices followed local high-yield cultivation standards.

1.2 Measurement Items and Methods

Leaf Area Index and Dry Matter Weight: At the jointing stage (May 8, 2014 and May 11, 2015), silking stage (June 8, 2014 and June 17, 2015), grain-filling stage (July 2, 2014 and July 12, 2015), and maturity stage (July 29, 2014 and July 26, 2015), five representative plants were selected from each plot. Leaf area was measured using the length-width coefficient method (correction coefficient 0.75) at jointing and silking stages. Aboveground plant parts were then separated into leaves, bracts (grain-filling and maturity stages), stems/sheaths, tassels (silking, grain-filling, and maturity stages), cobs (grain-filling and maturity stages), and grains (grain-filling and maturity stages). Samples were oven-dried at 105°C for 30 minutes, then at 80°C to constant weight before weighing.

Net Photosynthetic Rate and Transpiration Rate: At the jointing and silking stages, measurements were taken on clear mornings around 10:00 AM using a portable photosynthesis system LI-6400 (LI-COR, USA). The first fully expanded leaf from the top was measured at jointing stage, and the ear leaf was measured at silking stage. Controlled conditions were: CO concentration 400 µmol · mol ^{1}, temperature 30°C, and light intensity 1,200 µmol · m ^{2} · s ^{1}. Five leaves per treatment were measured with three repetitions each.

Yield Components and Grain Yield: At maturity, 20 consecutive ears were selected from each plot to measure ear length, ear diameter, rows per ear, grains per row, bare tip length, and 1000-kernel weight. Grain yield was calculated based on actual harvested plants per plot.

1.3 Parameter Calculation

Dry matter distribution ratio (%) for leaves (bracts, stems/sheaths, tassels, cobs, grains) = [dry weight of component (kg · hm ^{2}) / total aboveground dry weight (kg · hm ^{2})] × 100

1.4 Data Statistical Analysis Methods

All data presented are means of three replicates. Data were analyzed using DPS 7.05 and SPSS 19.0 software for analysis of variance, multiple comparisons, and correlation analysis.

2.1 Effects of Combined Silicon-Phosphorus Application on Leaf Area Index, Net Photosynthetic Rate, and Transpiration Rate

As shown in , no significant differences were observed between 'Zhenghong 2' and 'Zhenghong 115' in leaf area index (LAI), net photosynthetic rate (Pn), or transpiration rate at jointing and silking stages. However, fertilizer combinations significantly affected these parameters. In both years, phosphorus and silicon application significantly increased LAI and Pn, with phosphorus showing greater effects on Pn than silicon. Silicon application reduced leaf transpiration rate to varying degrees. In 2014, phosphorus application (P60) increased LAI and Pn by 22.53% and 6.18% at jointing stage, and 41.82% and 32.42% at silking stage (averaged across varieties), compared with no phosphorus. Silicon application (Si75) increased LAI and Pn by 12.03% and 8.92% at jointing stage, and 19.90% and 16.86% at silking stage, compared with no silicon. Combined silicon-phosphorus application (P60Si75) increased LAI and Pn by 41.88% and 15.64% at jointing stage, and 68.80% and 56.55% at silking stage, compared with the control (P0Si0), demonstrating clear complementary effects. Combined application produced the greatest increases in LAI and Pn while reducing transpiration rate for both varieties. Similar trends were observed in 2015.

2.2.1 Dry Matter Accumulation at Key Growth Stages

As shown in , no significant differences in dry matter accumulation were observed between 'Zhenghong 2' and 'Zhenghong 115' at jointing, silking, grain-filling, or maturity stages. Fertilizer combinations showed consistent effects on dry matter accumulation and harvest index for both varieties. Averaged across the four growth stages and both varieties, phosphorus application increased dry matter accumulation by 18.20% (2014) and 78.86% (2015) compared with no phosphorus. Silicon application increased dry matter accumulation by 12.61% (2014) and 20.98% (2015) compared with no silicon. Combined silicon-phosphorus application (P60Si75) increased dry matter accumulation by 34.74% (2014) and 121.23% (2015) compared with the control (P0Si0). In 2015, silicon, phosphorus, and combined applications all significantly increased harvest index. These results demonstrate that both phosphorus and silicon fertilizers can increase dry matter accumulation at key growth stages, with combined application showing significantly greater enhancement than either single application. Therefore, under low-phosphorus soil conditions, combined silicon-phosphorus application can substantially increase dry matter accumulation at critical growth stages, providing the material basis for high yield.

2.2.2 Dry Matter Accumulation During Different Growth Periods

As shown in , fertilization affected dry matter accumulation throughout the entire growth period, with accumulation during silking-maturity accounting for 47.35%-66.09% of total seasonal accumulation. Both varieties showed similar responses. In 2014, averaged across varieties, phosphorus (P60Si0), silicon (P0Si75), and combined (P60Si75) treatments increased dry matter accumulation during sowing-jointing by 42.72%, 31.38%, and 60.22%; during jointing-silking by 25.14%, 18.16%, and 28.96%; and during silking-maturity by 7.20%, 7.64%, and 16.70%, respectively, compared with the control (P0Si0). In 2015, the corresponding increases were 104.99%, 36.73%, and 159.44% for sowing-jointing; 63.41%, 19.26%, and 92.04% for jointing-silking; and 83.55%, 9.09%, and 85.08% for silking-maturity. Phosphorus showed greater effects than silicon, while combined application produced larger increases than either single application. The jointing-silking stage represents the critical period for rapid vegetative growth, functional development, and material accumulation, during which adequate nutrient supply is essential for maximizing grain yield. In summary, basal application of silicon and phosphorus fertilizers, particularly in combination, can significantly increase dry matter accumulation during key growth stages.

2.3 Dry Matter Distribution Characteristics in Organs During Late Growth Stages

As shown in , fertilizer combinations affected not only dry matter accumulation but also its distribution among organs during late growth stages, with consistent trends across varieties and years. Generally, silicon had smaller effects on distribution ratios than phosphorus. Phosphorus and combined applications tended to increase grain dry matter distribution ratios while decreasing leaf distribution ratios at grain-filling and maturity stages, particularly in 2015. Averaged across both varieties and years, phosphorus and combined applications increased grain distribution ratios at grain-filling and maturity stages by 21.64% and 5.33%, and 28.80% and 5.29%, respectively, compared with the control (P0Si0), while decreasing leaf distribution ratios by 22.24% and 8.24%, and 23.30% and 8.77%, respectively. Phosphorus and combined applications also reduced stem/sheath distribution ratios at grain-filling stage by 3.79% and 7.84%, respectively, but had minimal effects at maturity. Further analysis revealed that due to drought conditions in 2015, both harvest index and shelling percentage decreased compared with 2014, though appropriate phosphorus and combined silicon-phosphorus applications significantly increased shelling percentages for both varieties.

2.4 Grain Yield, Yield Components, and Ear Traits Under Combined Silicon-Phosphorus Application

As shown in and , fertilizer combinations significantly affected grain yield and yield components. Grain yield in 2015 was 42.20% lower than in 2014, averaged across both varieties. Both phosphorus and silicon applications increased grain yield, with phosphorus showing greater effects than silicon. Combined silicon-phosphorus application produced superior results compared with either single application, demonstrating clear synergistic effects. Averaged across both varieties and years, silicon alone, phosphorus alone, and combined application increased yield by 12.87%, 67.06%, and 86.27%, respectively, compared with the control (P0Si0). The yield increase was particularly large in 2015 due to extremely low control yields that year. The primary mechanisms for yield increase were enhanced plant growth, increased grains per ear (particularly grains per row) and ear length, improved grain filling, higher 1000-kernel weight, and reduced bare tip length. Combined analysis across both varieties and years revealed that grain yield was extremely significantly positively correlated with grains per ear (r = 0.958**) and 1000-kernel weight (r = 0.979**).

3 Discussion and Conclusion

Photosynthesis forms the basis for energy and material accumulation in maize, with leaf area index and net photosynthetic rate being important indicators of photosynthetic capacity, influenced by genotype and cultivation management. Phosphorus and silicon application can increase leaf area and photosynthetic rate. This study demonstrated that phosphorus, silicon, and combined applications all increased leaf area index and net photosynthetic rate at jointing and silking stages, with effects following the order: combined > phosphorus alone > silicon alone. This indicates that phosphorus is essential for plant energy metabolism and cannot be substituted, with adequate phosphorus nutrition being critical for high maize yields. Although the physiological and biochemical mechanisms of silicon in maize remain unclear, silicon application can enhance soil phosphorus availability and improve nitrogen, phosphorus, and potassium uptake, thereby promoting plant growth, increasing leaf area, enhancing photosynthetic enzyme activities, and ultimately increasing assimilate synthesis. At the jointing stage, all fertilization treatments significantly increased transpiration rate compared with the control. At jointing and silking stages, transpiration rate was higher under phosphorus application but lower under silicon application, suggesting that silicon deposition in leaves reduces ineffective water loss and improves water use efficiency, providing a foundation for efficient assimilate synthesis.

Adequate dry matter accumulation is essential for high maize yield, with grain yield being significantly positively correlated with dry matter accumulation within certain ranges. This study found significant positive correlations between grain yield and population dry matter accumulation at jointing, silking, grain-filling, and maturity stages (r = 0.753**, 0.766**, 0.625**, 0.580** in 2014 and r = 0.871**, 0.970**, 0.960**, 0.957** in 2015). Fertilization management effectively regulates dry matter accumulation and yield, with nitrogen, phosphorus, potassium, and silicon applications all significantly increasing maturity-stage dry matter accumulation and grain yield. This study showed that phosphorus and silicon applications increased dry matter accumulation and grain yield, following the order: combined > phosphorus alone > silicon alone. Despite severe drought during panicle development and pollination (late May to mid-June) and grain filling (July) in 2015, plus severe soil nutrient depletion from two previous seasons, which significantly reduced dry matter accumulation and yield across all treatments, the increments from combined silicon-phosphorus application relative to phosphorus alone were similar between years, with slightly higher increases in 2015. This indicates that continuous phosphorus application is crucial for meeting maize nutrient requirements in rain-fed low-phosphorus soils of Sichuan's hilly regions, while combined silicon application enhances drought and low-fertility tolerance, improves nitrogen, phosphorus, and potassium nutrition, increases dry matter accumulation, optimizes late-season dry matter distribution, and ultimately increases grain yield, demonstrating stable yield-enhancing effects.

Grain yield is also influenced by dry matter distribution and translocation among organs during mid-to-late growth stages, with distribution patterns shifting according to growth centers: leaves from emergence to pre-jointing, leaves and stems/sheaths from jointing to pre-pollination, and ears after pollination.

High-yielding varieties derive grain yield primarily from photosynthates produced during late growth stages. Dry matter distribution varies among genotypes and is affected by cultivation practices, with phosphorus and silicon applications altering distribution patterns. In Sichuan’ s hilly regions, stems and leaves continue accumulating matter for approximately 15 days after silking, with massive translocation to grains occurring only during mid-to-late grain filling. This study found that compared with phosphorus alone, combined silicon-phosphorus application did not significantly increase grain dry matter distribution ratio, but produced higher absolute grain dry matter accumulation due to greater total accumulation. Additionally, combined application increased ear length and diameter, significantly reduced bare tip length, and increased grains per ear and 1000-kernel weight. These results indicate that combined silicon-phosphorus application increases yield primarily by enhancing total dry matter accumulation, improving translocation to grains, promoting grain filling, and optimizing ear traits. In conclusion, combined silicon-phosphorus application increases photosynthetic capacity through larger leaf area and higher net photosynthetic rates, improves adaptation to low-phosphorus soils, enhances dry matter accumulation, optimizes late-season dry matter distribution among organs, promotes grain filling, improves ear traits, and ultimately increases grain yield.

References

[1] Wang Y H, Wang K R, Zhao R L, et al. Relationship between the source and sink of spring maize with high yield[J]. Scientia Agricultura Sinica, 2013, 46(2): 257-269

[2] Sun X F, Ding Z S, Hou H P, et al. Post-anthesis photosynthetic assimilation and the changes of carbon and nitrogen in different varieties of spring maize[J]. Acta Agronomica Sinica, 2013, 39(7): 1284-1292

[3] Li S, Peng Y F, Yu P, et al. Accumulation and distribution of dry matter and potassium in maize varieties released in different years[J]. Plant Nutrition and Fertilizer Science, 2011, 17(2): 325-332

[4] Liu W, Zhang J W, Lü P, et al. Effect of plant density on grain yield dry matter accumulation and partitioning in summer maize cultivar Denghai 661[J]. Acta Agronomica Sinica, 2011, 37(7): 1301-1307

[5] Zhan X M, Han X R, Yang J F, et al. Dynamics changes of dry matter accumulation of maize as affected by different quantity of nitrogen and phosphorus and potassium[J]. Chinese Journal of Soil Science, 2007, 38(3): 495-499

[6] Zhang R H, Hu F L, Yang X Q, et al. Effects of different cultivation patterns on photosynthetic characteristics and water use efficiency in dry land spring maize[J]. Acta Agronomica Sinica, 2013, 39(9): 1619-1627

[7] Chen Q R, Feng W Q, Tu S H, et al. Study on nutrient status in sloping uplands of Sichuan hilly areas[J]. Southwest China Journal of Agricultural Sciences, 2002, 15(1): 74-78

[8] Xu Z L, Gou X, Li K, et al. Distribution and characteristics of cultivated soil nutrients and its dynamic change trend in Sichuan Province[J]. Southwest China Journal of Agricultural Sciences, 2008, 21(3): 718-723

[9] National Bureau of Statistics of China. China Statistics Yearbook 2014[M]. Beijing: China Statistics Press, 2014: 457-461

[10] Vance C P, Uhde-Stone C, Allan D L. Phosphorus acquisition and use: Critical adaptations by plants for securing a nonrenewable resource[J]. New Phytologist, 2003, 157(3): 423-447

[11] Zhang F S, Wang J Q, Zhang W F, et al. Nutrient use efficiencies of major cereal crops in China and measures for improvement[J]. Acta Pedologica Sinica, 2008, 45(5): 915-924

[12] Wang X H, Cao Y J, Wei W W, et al. Phosphorus utilization characteristics of forty spring maize hybrids with high-yielding potential in north of China[J]. Plant Nutrition and Fertilizer Science, 2015, 21(3): 580-589

[13] Zhao C H, Pang H C, Li Y Y. Effect of interaction of water and phosphorus on maize growth and phosphorus accumulation in fluvo-aquic soil[J]. Plant Nutrition and Fertilizer Science, 2009, 15(1): 236-240

[14] Li S C, Hu C H, Gong J, et al. Effects of phosphorus supply on nitrogen and potassium absorption and distribution of maize with different phosphorus efficiency[J]. Plant Nutrition and Fertilizer Science, 2004, 10(3): 237-240

[15] Zhang A Q, He L Y, Men Y Y, et al. Effect of phosphorus levels on growth and nutrient absorption of low-P tolerant maize seedlings[J]. Chinese Journal of Applied and Environmental Biology, 2008, 14(3): 347-350

[16] Yuan S, Li C J, Peng Z P, et al. Effects of phosphorus on the plant growth, phosphorus cycling and distribution in different maize cultivars[J]. Plant Nutrition and Fertilizer Science, 2011, 17(2): 310-316

[17] Zhang K W, Li K P, Liu Z G, et al. Effect of phosphorus level on phosphorus absorption and utilization of different genotype maize seedlings[J]. Plant Nutrition and Fertilizer Science, 2007, 13(5): 795-801

[18] Li X Y, Sun L, WU L H. The distribution of silicon, nitrogen, phosphorus and potassium in the organs of different silicon-absorbing plants[J]. Chinese Journal of Soil Science, 2014, 45(1): 193-198

[19] Ma J F, Yamaji N. Silicon uptake and accumulation in higher plants[J]. Trends in Plant Science, 2006, 11(8): 392-397

[20] De Melo S P, Monteiro F A, De Bona F D. Silicon distribution and accumulation in shoot tissue of the tropical forage grass Brachiaria brizantha[J]. Plant

and Soil, 2010, 336(1/2): 231-239

[21] Tavakkoli E, English P, Guppy C N. Interaction of silicon and phosphorus mitigate manganese toxicity in rice in a highly weathered soil[J]. Communications in Soil Science and Plant Analysis, 2011, 42(5): 503-513

[22] Liu H X, Guo Z G. Effects of supplementary silicon on nitrogen, phosphorus and potassium contents in the shoots of Medicago sativa plants and in the soil under different soil moisture conditions[J]. Chinese Journal of Applied and Environmental Biology, 2011, 17(6): 809-813

[23] Xie Z M, Song R, Shao H B, et al. Silicon improves maize photosynthesis in saline-alkaline soils[J]. The Scientific World Journal, 2015, doi: 10.1155/2015/245072

[24] Yang C G, Dou H, Liang Y C, et al. Influence of silicon on cadmium availability and cadmium uptake by maize in cadmium-contaminated soil[J]. Scientia Agricultura Sinica, 2005, 38(1): 116-121

[25] Gong J L, Hu Y J, Long H Y, et al. Effect of application of silicon at different periods on grain yield and silicon absorption, use efficiency in super rice[J]. Scientia Agricultura Sinica, 2012, 45(8): 1475-1488

[26] Lu F Y, Jiang L G, Qin H D, et al. Effects of nitrogen and silicon levels on grain yield and qualities of rice[J]. Plant Nutrition and Fertilizer Science, 2005, 11(6): 846-850

[27] Zhang Y L, Wang Y L, Tan J F, et al. Effect of nitrogen application combined with silicon on the lodging-resistance and the yield of summer corn[J]. Journal of Maize Sciences, 2012, 20(4): 122-125

[28] Zhou Q, Pan G Q, Shi Z J, et al. Increasing production efficiency of using Si and the influence on quality of population in maize[J]. Journal of Maize Sciences, 2012, 10(1): 81-83

[29] Yang Y, Shi H C, Ke Y P, et al. Study on low-P tolerance of some maize inbred lines and hybrids[J]. Journal of Maize Sciences, 2007, 15(5): 12-16

[30] Yang Y, Li J W, Shi H C, et al. Alleviation of silicon on low-P stressed maize (Zea mays L.) seedlings under hydroponic culture conditions[J]. World Journal of Agricultural Sciences, 2008, 4(2): 168-172

[31] Owino-Gerroh C, Gascho G J. Effect of silicon on low pH soil phosphorus sorption and on uptake and growth of maize[J]. Communications in Soil Science and Plant Analysis, 2005, 35(15/16): 2369-2378

[32] Li R Y, Shen X H, Xie X J, et al. Effect of silicon application on phosphorus translocation in soil-rice system[J]. Acta Pedologica Sinica, 2014, 51(2): 423-428

[33] Mehrabanjoubani P, Abdolzadeh A, Sadeghipour H R, et al. Silicon affects transcellular and apoplastic uptake of some nutrients in plants[J]. Pedosphere,

2015, 25(2): 192-201

[34] Zhu C H, Xie M L, Guo P, et al. Effects of phosphorus and silicon application on uptake and utilization of N, K by maize[J]. Chinese Journal of Soil Science, 2015, 46(6): 1489-1496

[35] Peng Z P, Zhang J T, Yuan S, et al. Effects of different phosphrus application rates on the dynamic accumulation and distribution of dry matter and phosphrus in maize[J]. Plant Nutrition and Fertilizer Science, 2009, 15(4): 793-798

Note: Figure translations are in progress. See original paper for figures.