Chapter 11
Effect of Silicon on Crop Growth, Yield and Quality

Abstract  Silicon (Si) has widely been reported to increase the growth and biomass, yield and quality of a broad range of crops including monocotyledonous crops such as rice, wheat, maize, barley, millet, sorghum and sugarcane that actively take up and accumulate high amounts of Si in their organs and some dicotyledonous crops such as cotton and some vegetable and fruit crops. The yield increment, however, may be attributable not only to the beneficial effects of Si including growth promotion, lodging resistance and biotic and abiotic stress resistance but also to some indirect effects such as pH adjustment and acquisition of macro- and micronutrients contained in the silicate fertilizers, especially when slags or Si-containing mineral ores are used as sources of silicate fertilizer.

Keywords  Growth • Photosynthesis • Nutrient uptake • Quality • Silicon • Yield

11.1 General

It has been well documented that silicon (Si) is effective in enhancing the growth and yield of many crops of agricultural and horticultural importance (for review, see Lian 1976; Elawad and Green 1979; Savant et al. 1997, 1999; Wang et al. 2001; Singh et al. 2005; Guntzer et al. 2012). The major crops that are widely reported to positively respond to Si fertilization include some monocotyledonous crops such as rice (*Oryza sativa*), wheat (*Triticum aestivum*), maize (*Zea mays*), barley (*Hordeum vulgare*), millet (*Setaria italica*), sorghum (*Sorghum bicolor*) and sugarcane (*Saccharum officinarum*) that actively absorb and accumulate high amount of Si in their organs and some dicotyledonous crops such as cotton (*Gossypium*), soybean (*Glycine max*) and some vegetable and fruit crops that are also able to accumulate Si through specific transporters (see Chap. 4). Table 11.1 shows the effect of large-scale field application of blast furnace slag-based silicate fertilizer on crop yield and economic benefit indicated by ratio of added revenue to Si fertilizer cost in northeastern China during 2005–2006 (Y. Liang et al., unpublished). The data from Table 11.1 clearly show that although the average yield increase percent for all the crops tested except maize due to Si fertilizer application was above 10 %, the ratio of benefit to cost differed greatly with crop species mainly due to the per unit area crop yield and the price of the products. Although the average yield increase percent for
soybean (11%) was statistically significant compared with Si-untreated control application of Si fertilizer was still less acceptable by local farmers because of its lower economic benefit (lower ratio of benefit to Si fertilizer cost). The application of Si fertilizer to greenhouse-grown cucumber (Cucumis sativus) and tomato (Lycopersicon esculentum) led to extremely high economic benefits and thus was welcomed commercially (Table 11.1).

### Table 11.1
The effect of field application of blast furnace slag-based silicate fertilizer on crop yield and benefit/cost ratio during 2005–2006 in northeastern China (Y. Liang et al., unpublished)

<table>
<thead>
<tr>
<th>Crops tested</th>
<th>Yield increase percent range</th>
<th>Average yield increase (%)</th>
<th>Benefit/cost ratio</th>
<th>No. of trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td>3.5–28.5</td>
<td>10.3**</td>
<td>4.4</td>
<td>50</td>
</tr>
<tr>
<td>Maize</td>
<td>5.6–10.4</td>
<td>7.7*</td>
<td>3.1</td>
<td>44</td>
</tr>
<tr>
<td>Cucumber</td>
<td>9.35–25.6</td>
<td>13.7**</td>
<td>42.9</td>
<td>40</td>
</tr>
<tr>
<td>Tomato</td>
<td>8.7–15.9</td>
<td>12.0**</td>
<td>35.7</td>
<td>35</td>
</tr>
<tr>
<td>Soybean</td>
<td>7.5–13.6</td>
<td>11.0**</td>
<td>1.7</td>
<td>32</td>
</tr>
</tbody>
</table>

* and ** indicate significantly different at P<0.05 and P<0.01, respectively, compared with Si-untreated controls

soybean (11%) was statistically significant compared with Si-untreated control application of Si fertilizer was still less acceptable by local farmers because of its lower economic benefit (lower ratio of benefit to Si fertilizer cost). The application of Si fertilizer to greenhouse-grown cucumber (Cucumis sativus) and tomato (Lycopersicon esculentum) led to extremely high economic benefits and thus was welcomed commercially (Table 11.1).

### 11.1.1 Si-Improved Growth and Yield of Monocotyledonous Crops

#### 11.1.1.1 Rice

Field application of slag-based silicate fertilizers in rice paddy field started in Japan in the early 1950s and in South Korea in the 1960s–1970s. This practice contributed greatly to rice production sustainability and food security in these countries (Savant et al. 1997; Park 2001; Ma and Takahashi 2002; also see Chap. 1). The use of silicate fertilizers is also a rather common agricultural practice to increase the growth and yield of rice in Southeast Asia including China mainland, Chinese Taiwan, Thailand, the Philippines, Ceylon, Vietnam, Sri Lanka, Pakistan, India and Indonesia and in Central, South and North America, including Florida, Colombia and Brazil, and in West Africa, including Nigeria (Lian 1976; Snyder et al. 1986; Yamauchi and Winslow 1989; Datnoff et al. 1992; Winslow 1992; Liang et al. 1994; Savant et al. 1997; Winslow et al. 1997; Alvarez and Datnoff 2001a; Correa-Victoria et al. 2001; Korndörfer and Lepsch 2001; Prabhu et al. 2001). Lian (1976) and Elawad and Green (1979) reviewed the rice yield responses to Si fertilization, mostly in temperate regions such as Japan, Korea and Chinese Taiwan, while Savant et al. (1997) summarized the positive effects of Si fertilization on the growth and yield of rice grown on highly weathered soils such as inceptisols, alfisols, ultisols and oxisols in the subtropical to tropical zones. In these areas more beneficial effects of Si on rice could be expected due to low Si bioavailability. In addition to lowland rice,
beneficial effects of Si fertilization on the yields of upland rice have also been reported in the Philippines, China, Colombia, Brazil and West Africa (IRRI 1965, 1966; Yamauchi and Winslow 1989; Datnoff et al. 1992; Winslow 1992; Liang et al. 1994; Savant et al. 1997; Correa-Victoria et al. 2001; Prabhu et al. 2001).

Si fertilization is reported to increase the growth of rice plants during the entire growth stage, benefiting rice plants not only in the nursery (at seedling stage) but also in the field after transplanting (IRRI 1965, 1966; Liang et al. 1994). It was reported that the application of various slags to nursery plants led to an increase in the number of leaves and dry matter yield of rice (Savant et al. 1997 and references therein). The application of black to grey ash of rice hulls improved the growth of rice seedlings and biomass (Sawant et al. 1994; Savant et al. 1997). After transplanting, Si fertilization increased the number of tillers and panicles (IRRI 1965, 1966; Liang et al. 1994). Ma et al. (1989) reported that the dry weight of straw and grain in rice plants not receiving Si during the reproductive stage decreased by 20% and 50%, respectively, compared with those of plants receiving Si throughout the growth period. When Si was supplied at the reproductive stage, the dry weight of rice straw and rice grain was increased by 243% and 30%, respectively. Regardless of whether Si was supplied or not, its effect was limited to the vegetative and ripening stages. The percentage of filled spikelets was also affected by the addition of Si during the reproductive stage, while the 1,000-grain weight was not influenced. These results suggest that the supply of Si during the reproductive stage is crucially important for the growth of rice plants.

More recently, Wang et al. (2014) reported the beneficial effects of steel slag applied at various rates on rice growth, yield and soil properties in a subtropical paddy field of China (Table 11.2). They showed that while steel-slag amendment had no positive effects on rice growth characteristics other than the shoot/root ratio \( (P<0.05) \), it significantly increased the grain yield and percentage of ripened grain (Table 11.2). Further research showed that the yield of the first early rice crop was significantly higher when slag was applied at a rate of 8 Mg ha\(^{-1}\) than when lower rates were applied \( (P<0.05, \text{Table 11.3}, \text{Wang et al. 2015}) \), and the yield of the late rice crop with slag added at a rate of 4 and 8 Mg ha\(^{-1}\) was also significantly higher than in the control \( (P<0.05) \); however, no significant rice yield response was observed when steel slag was applied at a rate of 2 Mg ha\(^{-1}\) only \( (P>0.05) \). Furthermore, no significant residual effects of slag application were observed on the yields of both the second early paddy and the vegetable crops, suggesting that application of slag is needed for the third crop season. On the other hand, slag effects on rice yield may be caused partly by its indirect effect, as could be seen from Table 11.2 that soil organic carbon (C), total nitrogen (N), total phosphorus (P), total iron (Fe), total manganese (Mn), available \( \text{P}_2\text{O}_5 \), available \( \text{SiO}_2 \) and ferric Fe contents increased significantly with the application levels of steel slag. Agarie et al. (1992) investigated the effects of Si and light intensity on the growth and dry mass of three rice cultivars and found that Si applications promoted seedling growth and dry mass accumulation. The effect of Si on growth improvement was dependent on light exposition (canopy) and the cultivars tested; the shade-resistant cultivar, cv. Koshihikari, responded the best to Si amendment in shade conditions. The beneficial
The effects of Si may be attributed to an increase in water use efficiency (WUE) and maintenance of photosynthetic activity. At the cell level, the growth promotion by the addition of Si in rice has been linked to enhanced cell elongation, but not cell division in the epidermal cells (Hossain et al. 2002). Isa et al. (2010) found that Si-enhanced rice growth was independent of silica deposition and suggested an important physiological role of Si in the cell wall, although they did not report any evidence.

### Table 11.2 Rice growth and yield characteristics and soil properties of plots amended with different rates of steel slag

<table>
<thead>
<tr>
<th>Application level (mg ha⁻¹)</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Growth characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total dry matter (Mg ha⁻¹)</td>
<td>17.20 ± 0.45</td>
<td>17.32 ± 0.27</td>
<td>17.46 ± 0.29</td>
<td>17.56 ± 0.25</td>
</tr>
<tr>
<td>Shoot biomass (Mg ha⁻¹)</td>
<td>14.94 ± 0.30</td>
<td>14.95 ± 0.22</td>
<td>15.06 ± 0.49</td>
<td>15.06 ± 0.52</td>
</tr>
<tr>
<td>Root biomass (Mg ha⁻¹)</td>
<td>2.31 ± 0.19</td>
<td>2.36 ± 0.16</td>
<td>2.37 ± 0.09</td>
<td>2.50 ± 0.16</td>
</tr>
<tr>
<td>Shoot/root ratio</td>
<td>6.42 ± 0.04ᵇ</td>
<td>6.30 ± 0.16ᵇ</td>
<td>6.17 ± 0.07ᵇ</td>
<td>6.08 ± 0.07ᶜ</td>
</tr>
<tr>
<td><strong>Yield characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain yield (Mg ha⁻¹)</td>
<td>8.09 ± 0.15ᵇ</td>
<td>8.22 ± 0.13ᵇ</td>
<td>8.33 ± 0.12ᵇ</td>
<td>8.43 ± 0.09²</td>
</tr>
<tr>
<td>1,000-grain weight (g)</td>
<td>24.37 ± 0.55</td>
<td>24.19 ± 0.19</td>
<td>24.29 ± 0.75</td>
<td>24.37 ± 0.49</td>
</tr>
<tr>
<td>Ripened grains (%)</td>
<td>0.85 ± 0.00ᵇ</td>
<td>0.85 ± 0.01ᵇ</td>
<td>0.87 ± 0.01ᵃ</td>
<td>0.87 ± 0.01ᵃ</td>
</tr>
<tr>
<td><strong>Soil properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>6.48 ± 0.13</td>
<td>6.81 ± 0.12ᵇ</td>
<td>6.93 ± 0.37</td>
<td>7.16 ± 0.66</td>
</tr>
<tr>
<td>Bull density (g cm⁻³)</td>
<td>1.05 ± 0.10</td>
<td>1.04 ± 0.07</td>
<td>0.95 ± 0.03</td>
<td>0.97 ± 0.04</td>
</tr>
<tr>
<td>Organic C (g kg⁻¹)</td>
<td>18.10 ± 0.28ᵇ</td>
<td>18.07 ± 0.16ᵇ</td>
<td>18.53 ± 0.09ᵇᵇ</td>
<td>18.89 ± 0.35ᵃ</td>
</tr>
<tr>
<td>Total N (g kg⁻¹)</td>
<td>1.17 ± 0.08ᵇ</td>
<td>1.43 ± 0.12ᵃ</td>
<td>1.40 ± 0.12ᵃ</td>
<td>1.40 ± 0.04ᵃ</td>
</tr>
<tr>
<td>Total P (g kg⁻¹)</td>
<td>1.06 ± 0.04ᵇ</td>
<td>1.39 ± 0.09ᵃ</td>
<td>1.17 ± 0.13ᵃᵇ</td>
<td>1.19 ± 0.04ᵇᵇ</td>
</tr>
<tr>
<td>Total Fe (g kg⁻¹)</td>
<td>23.35 ± 0.58ᵇ</td>
<td>26.57 ± 159ᵇ</td>
<td>27.84 ± 1.76ᵃ</td>
<td>27.79 ± 1.10ᵃ</td>
</tr>
<tr>
<td>Total Mn (mg kg⁻¹)</td>
<td>216.60 ± 0.18ᵇ</td>
<td>244.81 ± 6.82ᵇ</td>
<td>293.39 ± 18.17ᵃ</td>
<td>314.23 ± 25.26ᵃ</td>
</tr>
<tr>
<td>Available P₂O₅ (mg kg⁻¹)</td>
<td>53.12 ± 1.24ᵃ</td>
<td>65.05 ± 2.76ᶜ</td>
<td>79.85 ± 7.62ᵇ</td>
<td>96.37 ± 3.03ᵃ</td>
</tr>
<tr>
<td>Available SiO₂ (mg kg⁻¹)</td>
<td>254.09 ± 5.12ᵇ</td>
<td>485.34 ± 750ᵇᶜ</td>
<td>764.00 ± 15.35ᵇ</td>
<td>1232.37 ± 226.04ᵇ</td>
</tr>
<tr>
<td>Ferric Fe (g kg⁻¹)</td>
<td>3.18 ± 0.18ᵃ</td>
<td>4.66 ± 0.49ᵇᶜ</td>
<td>5.75 ± 0.77ᵇ</td>
<td>8.76 ± 1.53ᵃ</td>
</tr>
</tbody>
</table>

From Wang et al. (2014)
Different letters in a single row indicate statistical differences (P<0.05)

### Table 11.3 Yields of crops amended with various rates of steel slag

<table>
<thead>
<tr>
<th>Crop yield (Mg ha⁻¹)</th>
<th>Application level (Mg ha⁻¹)</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>First early rice crop</td>
<td>8.09 ± 0.15ᵃ</td>
<td>822 ± 0.13ᵇᵇ</td>
<td>8.33 ± 0.12ᵇᵇ</td>
<td>8.43 ± 0.09ᵇᵇ</td>
<td></td>
</tr>
<tr>
<td>Late rice crop</td>
<td>7.46 ± 0.16ᵃ</td>
<td>7.49 ± 0.12ᵃ</td>
<td>8.08 ± 0.34ᵇᵇ</td>
<td>8.14 ± 0.28ᵇᵇ</td>
<td></td>
</tr>
<tr>
<td>Vegetable crop</td>
<td>26.9 ± 2.8ᵃ</td>
<td>26.9 ± 1.9ᵃ</td>
<td>27.0 ± 3.2ᵃ</td>
<td>27.0 ± 42ᵃ</td>
<td></td>
</tr>
<tr>
<td>Second early rice crop</td>
<td>7.87 ± 0.09ᵃ</td>
<td>7.78 ± 0.11ᵃ</td>
<td>7.93 ± 0.12ᵃ</td>
<td>7.84 ± 0.09ᵃ</td>
<td></td>
</tr>
</tbody>
</table>

From Wang et al. (2015)
Different letters within a row indicate statistical differences (P<0.05)

effects of Si may be attributed to an increase in water use efficiency (WUE) and maintenance of photosynthetic activity. At the cell level, the growth promotion by the addition of Si in rice has been linked to enhanced cell elongation, but not cell division in the epidermal cells (Hossain et al. 2002). Isa et al. (2010) found that Si-enhanced rice growth was independent of silica deposition and suggested an important physiological role of Si in the cell wall, although they did not report any evidence.
The yield responses to Si fertilization depend largely upon plant-available Si content in soil, plant-available Si content of the fertilizers used, soil pH, N application levels and other environmental factors such as climate conditions (Liang et al. 1994; Savant et al. 1997; Park 2001; Wang et al. 2001, 2014, 2015). According to the review by Savant et al. (1997), rice yield responses to Si fertilization differed greatly from one experiment to another, ranging from 4.6 to 48%. In 16 provinces of China, yield increment caused by Si fertilization ranged from 0 to 400% with an average of 10%, depending on the severity of Si deficiency in the soils tested (Wang et al. 2001). Large-scale field experiments (about 76 million ha) at 50 trial sites across northeast China show that amendment of furnace slag-based calcium silicate fertilizers to paddy soils derived from bleaching-meadow soil, meadow soil, bleaching soil, chernozem and black soil showed a significantly positive yield increase ranging from 3.5 to 28.5% with an average of 10.3% (Y. Liang et al. unpublished; see Table 11.1). Interestingly, a yield increase of as high as 76% due to the application of Si at 3 t/ha in a form of furnace phosphorus slag was reported for upland rice grown on an inceptisol with pH 4.7 and Al saturation of 18% at the Santa Rosa site of Colombia (Correa-Victoria et al. 2001). However, it should be stressed that the yield increment was attributable not only to the beneficial effects of Si including growth promotion, lodging resistance, disease and pest resistance and abiotic stress resistance but also to some indirect effects such as pH adjustment and acquisition of macro- and micronutrients contained in the Si fertilizers (e.g. slag-based Si fertilizer and potash feldspar or potash-rich minerals manufactured by calcination or hydrothermal chemical reaction method). Another important issue that needs to be emphasized is associated with residual effects or after-effect of slag-based Si fertilizers and feldspar- or potash-rich mineral-based Si fertilizers because these categories of fertilizers are characterized by their slow-releasing properties. Thus, yearly applications may not be needed and the subsequent application rates can be considerably reduced (Datnoff et al. 1997; Correa-Victoria et al. 2001). For example, Si applications in a rice–sugarcane (Saccharum officinarum) rotation in southern Florida resulted in increased yields of both rice and sugarcane that was grown immediately after rice (Alvarez and Datnoff 2001b). Correa-Victoria et al. (2001) also reported that the application of slag in Colombia increased upland rice yield by 100% due to its residual effect.

11.1.1.2 Wheat

Wheat is another staple food crop that is widely reported to positively respond to silicate fertilizers (Wang et al. 2001) and that also has an active uptake and accumulation of Si in plant organs (Rafi and Epstein 1999; Montpetit et al. 2012). Zhu and Chen (1963) reported an obvious yield increase in wheat ranging from 6 to 12% following the application of steel-slag-based calcium silicates in northern China. Subsequent field trials conducted across China also showed significantly positive yield responses to application of silicate fertilizers (ranging from 5 to 12%) (Wang et al. 2001). In other instances, consecutive four-year field trials indicated that the
application of a mixture of powdered sodium metasilicate and sodium disilicate increased wheat yield by 4.1–9.3 % on a calcareous paddy soil (Liang et al. 1994). Liu et al. (2011) also conducted long-term field trials with slow-released potassium silicate and showed that wheat yield was increased by 13.8 % on the average.

Xia et al. (1999) and Cui et al. (1999) observed a ca. 10 % yield increase when Si was applied by foliar spray and as a soil amendment. Yu and Gao (2012) investigated the effects of Si on the yield of two wheat cultivars and found that appropriate Si levels could increase the grain yield of wheat, and the increase resulted from the increase in spike number and grain number per spike. By contrast, Segalin et al. (2013) tested the effect of foliar applications of Si on wheat yield and quality and did not observe any improvement in five cultivars. This may be related to the fact that foliar applications did not lead to Si accumulation in wheat as reported by Guével et al. (2007).

11.1.1.3 Sugarcane

Sugarcane is a Si-accumulating plant species and the second most Si-responsive crop after rice. Samuels (1969) reported that the aboveground parts of 12-month-old sugarcane plants contained 379 kg ha$^{-1}$ of Si, compared to 362 kg ha$^{-1}$ of K and 140 kg ha$^{-1}$ of N. As a result, Si deficiency in soils could be a yield-declining factor in sugarcane, resulting in symptoms such as twisted leaves and leaf freckling (Wang et al. 2001). It has been well documented that Si nutrition has a definite agronomic role in sugarcane crop cultivation, especially on highly weathered tropical soils such as oxisols, ultisols, entisols and histosols (organic soils) (for review, see Savant et al. 1999; Meyer and Keeping 2001). Earlier field trials conducted in Hawaii, Mauritius, Puerto Rico, Florida, South Africa, Brazil and Australia demonstrated that the use of silicate slag as a source of Si for sugarcane increased yield by 10–50 % on Si-low soils (Ayres 1966; Clements 1965; Fox et al. 1967; Samuels 1969; Cheong and Halais 1970; Haysom and Chapman 1975; Gascho 1976; Elawad et al. 1982; Anderson et al. 1991; Alvarez and Datnoff 2001b; Meyer and Keeping 2001; Berthelsen et al. 2001). Similar results were obtained in Asia including China, Chinese Taiwan, Indonesia, Malaysia and Pakistan (Savant et al. 1999 and the references therein; Wang et al. 2001; Ashraf et al. 2009). The review of the literature by Savant et al. (1999) unveiled several levels of Si-caused yield increases in cane ranging from 10 to 50 % and from 5 to 35 %. Some recent trials in China also gave positive cane yield responses to application of Si fertilizer. For example, Jiang et al. (2011) found that the application of Si (720 kg SiO$_2$ ha$^{-1}$) increased the sugarcane and sugar yields by 9.0 % and 9.7 %, respectively. Huang et al. (2011) also found that sugarcane yield was significantly increased by application of Si.

The observed positive sugarcane responses to Si fertilization have been attributable to a number of factors including prevention of aluminium and manganese toxicities in highly weathered acid soils, improved water use efficiency, protection from fungal and insect pest damage, improved phosphorus nutrition, improved mechanical strength and improved photosynthesis through better use of sunlight (Anderson et al. 1991; see also Chaps. 5, 7, 9 and 10). For instance, Zeng et al.
(2007) found that Si application could increase the chlorophyll content and activity of nitrate reductase of lower (old) leaves of sugarcane, prolong the leaf functional period and increase the population leaf area index. Si also increased the export of photosynthetic products from middle and lower leaves at night.

Application of Si can influence the availability of nutrients in the soil and nutrient concentrations in sugarcane plants. Huang et al. (2011) observed that the application of Si increased the levels of soil-available Si and exchangeable calcium (Ca) and magnesium (Mg), but decreased the soil organic matter and available P content. Huang et al. (1992) found that Si promoted the translocation of 11 nutrients including N, P, potassium (K), Mg, Ca, Mn, zinc (Zn), copper (Cu), Fe, molybdenum (Mo) and boron (B) to the growing parts of the plant, which could enhance the growth of sugarcane, as well as sugar synthesis and accumulation. Huang et al. (1997) also observed increased concentrations of N and K in leaves following Si application, but the effects on P concentrations were different in different trial sites. The authors suggested that Si could improve the P status in the leaves, depending on the soil P level. These studies suggest that some of the beneficial effects of Si on sugarcane growth are indirect and related to Si-mediated improvement in availability of nutrients in the soil and nutrient uptake by plants.

Si may play a role in the synthesis, storage and retention of sucrose in sugarcane plants. Ji et al. (1992) observed that Si application decreased the activities of acid invertase in mature leaves, but increased the activities of neutral invertase at elongation and maturity stages. Si-mediated changes facilitated sucrose accumulation in the cane. Pawar et al. (2003) observed that foliar applications of Si increased the sucrose synthase and sucrose phosphate synthase activities in the leaves, although the mean commercial sugar content was not changed.

The improvement of sugarcane yields by Si may also be attributed to its induced resistance to various biotic and abiotic stresses, as has been discussed in previous chapters. The cane yield responses to Si fertilization are more significant under environmental stress than under normal conditions. Also, the cane yield response is genotype dependent. For instance, cane yield was increased with Si addition by 59% and 28% in the salt-sensitive and salt-tolerant genotype, respectively, compared with the controls (Ashraf et al. 2009).

### 11.1.1.4 Maize

Maize is also one of the cereal crops that actively take up and accumulate Si into its organs (Liang et al. 2006; Mitani et al. 2009; see Chap. 4). Maize growth and yield are also highly responsive to Si fertilization (Yuan et al. 1996; Li et al. 1999; Wang et al. 2001 and references therein; Liu et al. 2011; also see Table 11.1). As early as the 1960s, Zhu and Chen (1963) conducted field trials on maize with steel slag in Liaoning province of northern China and reported a yield increment ranging from 8.5 to 10.2%. By conducting 8 field trials on maize in northern China, Li et al. (1999) showed that the yield of summer maize receiving Si fertilization was increased by 473–900 kg ha⁻¹ over the control (P<0.01). The application of Si fertilizer significantly increased concentrations of N, P, Zn and Mn in maize plants.
Thus, the yield response to Si may be related to improved uptake of these nutrients (Li et al. 1999). Yuan et al. (1996) agreed that the positive maize yield responses to Si fertilization could be attributable to the increased ear numbers and grain size. Consecutive field trials indicated that, on the average, the application of Si fertilizer resulted in maize yield increase by 7.3% (Liu et al. 2011) and by 7.7% (Y. Liang et al., unpublished, Table 11.1).

Maize yield responses to Si fertilization may be impacted by climate and plant-available Si in soils as well. According to Li et al. (1999), the application of Si resulted in a maize yield increase by 10% in 1997 due to a severe drought stress during maize-growing season, while yield increment of 5% was observed in 1998 when no drought stress occurred. It seems to suggest that the beneficial effects of Si on plant growth and yield are particularly distinct under drought stress conditions.

11.1.2 Dicotyledonous Crops

11.1.2.1 Cucumber

Cucumber is a typical intermediate type of plant species that also actively takes up and accumulates Si into its organs (Liang et al. 2006; Nikolic et al. 2007). Beneficial effects of Si on cucumber, especially under biotic and abiotic stress, have been most widely reported (Miyake and Takahashi 1983a, b; Adatia and Besford 1986; Marschner et al. 1990; Chérif and Bélanger 1992; Wang et al. 2007; Pavlovic et al. 2013; Liu et al. 2014; also see Chaps. 5, 8 and 9). Four-year field trials show that, on the average, the application of slag-based silicate fertilizers to greenhouse cucumber increased the yield by 13.7% (Y. Liang et al., unpublished, Table 11.1). The beneficial effect of Si on the seed germination of cucumber has also been reported. For example, Li and Ma (2002) reported that when the available Si in soil was in the range of 55 to 203 mg kg\(^{-1}\), the activities of both protease and lipase and respiration rate were obviously increased during seed germination. The seed vigour was also increased. These results clearly show that suitable Si level could enhance the seed germination of cucumber.

During seedling growth, Li and Ma (2002) observed Si-mediated increases of the photosynthetic rate, root activities and nitrate reductase activity. In a pot trial, Wang et al. (2007) observed that applications of Si up to 125 mg kg\(^{-1}\) improved leaf chlorophyll levels, photosynthetic rate and water use efficiency. Similar results have recently been observed in a hydroponic experiment (Liu et al. 2014).

11.1.2.2 Tomato

Although tomato (Solanum lycopersicum) is a typical Si-excluder plant species as compared to rice, a typical Si accumulator (Nikolic et al. 2007), Si fertilization has been reported to increase the growth and yield (Liang et al. 1993; Liu 1997; Liu
et al. 2011, Table 11.1). Liang et al. (1993) showed that adding 50 μg Si L−1 to a nutrient solution increased tomato yield by 62 %. Furthermore, field trials indicated that Si fertilization increased tomato yield by up to 15–30 % due to increased fruit numbers and sizes (Liang et al. 1993; see Table 11.1). Tomato fruits became ripened four days earlier with higher commercially produced tomato yield due to Si fertilization compared with the control treatment (Liang et al. 1993). Liu (1997) conducted several field trials to compare the effects of Si and Ca fertilizer on tomato growth, yield and quality. The results showed that the application of Si fertilizer significantly increased tomato resistance to diseases, fruit size and consequently yield. In addition, the combined application of Si–Ca fertilizer improved the taste of tomato fruit due to increased sugar content, which was not observed if only Ca fertilizer was added without Si fertilization. Cao et al. (2013) investigated the effects of different levels of Si on growth and H2O and CO2 exchange of tomato grown hydroponically and found that 0.6 mM (T1) and 1.2 mM Si (T2) significantly increased the plant height and dry mass of roots, stem and leaves. The contents of photosynthetic pigments (such as chlorophyll a and b and carotenoid) are also increased by applied Si at both T1 and T2 levels. However, a higher concentration of Si at 1.8 mM Si (T3) did not improve the plant growth or contents of photosynthetic pigments. The leaf net photosynthetic rates were also increased at both T1 and T2 Si levels as compared to the control, but it was slightly decreased by applied Si at T3 level. The leaf transpiration rate is decreased at all the three levels of Si tested. Si application also increased the instantaneous water use efficiency.

The form of Si influences its effect on tomato growth. Xue et al. (2012) observed that foliar application of both inorganic and organic Si could enhance the growth of tomato seedlings and increase single tomato fruit weight, with the promotion being more obvious by application of inorganic Si.

11.1.2.3 Others

Recently, Si fertilizers have been applied to many other crops of agricultural and horticultural importance (for review, see Wang et al. 2001; Korndörfer and Lepsch 2001). For example, field trials with slag-based silicate fertilizers showed that soybean responded positively with its averaged yield increase of 11 % (Y. Liang et al. unpublished; see Table 11.1). Long-term field trials in 26 provinces of China demonstrated that on the average, the application of a slow-released potassium silicate formulation increased the yield of potato (Solanum tuberosum) by 12.3 %, peanut (Arachis hypogaea) by 6.7 %, radish (Raphanus sativus) by 11.2 %, soybean by 5.1 %, green bean (Phaseolus vulgaris) by 6.0 %, sugar beet (Beta vulgaris) by 4.7 %, cabbage (Brassica oleracea) by 15.2 %, chilli pepper (Capsicum annuum) by 8.4 %, pumpkin (Cucurbita maxima) by 11.7 %, peach (Prunus persica) by 18.1 %, grapevine (Vitis vinifera) by 6.5 %, banana (Musa sp.) by 4.8 %, citrus species by 12.3 %, longan (Dimocarpus longan Lour) by 10.7 %, tea (Camelia sinensis) by 11.0 %, ginseng (Panax ginseng) by 3.2 % and papaya (Carica papaya) by 9.7 % (Liu et al. 2011). Balakhnina et al. (2012) observed that the application of Si
stimulated the growth and biomass production of both shoot and roots in barley. In citrus, the application of Si fertilizers enhanced the growth by 30–80 %, promoted fruit maturation by 2–4 weeks and improved fruit quantity (Meena et al. 2014, and reference therein). Li and Ma (2003) found that, within a suitable range of Si application rates, the growth of cotton seedlings was promoted. Meanwhile, the uptake of P, Zn and B in seedlings was enhanced, while the uptake of N, K, Mn, Ca and Mg was decreased. These results suggest that Si could improve the nutritional metabolism of cotton plants and therefore the growth. Si application also affected the floricultural quality of gerbera. Kamenidou et al. (2010) found that Si-applied gerbera plants had thicker flower peduncles and increased flower diameters and height. Furthermore, the gerbera plants treated with Si flowered earlier than the controls.

Crop yield responses to Si fertilizers are more evident under various forms of abiotic and biotic stresses than under normal conditions.

11.2 Crop Quality

Si fertilization is proven not only to enhance crop growth and yield but also to improve crop quality. Si fertilizers are mainly reported to improve the quality of rice grain, sugarcane, vegetables and fruits. For instance, brown rice rate, milled rice rate and head rice rate coupled with fatty acid content were significantly higher in Si-treated rice than in the Si-untreated rice, while chalky grain rate and chalkiness were lower (Zhang et al. 2007; Shang et al. 2009). Yu and Gao (2012) investigated the effects of Si on grain quality in two wheat cultivars and found that Si application did not affect the 1,000-grain weight and protein content of grain in the two cultivars tested; on the other hand, in cv. Longmai 26, Si application enhanced the content of wet gluten, flour water absorption and paste fracture time, and the extension quality of paste was also improved. Sugarcane juice quality characteristics like Brix (% soluble solids in juice), Pol (% sucrose in juice), commercial cane sugar (CCS) and sugar recovery in both salt-sensitive and salt-tolerant sugarcane genotypes were also significantly improved by Si (Ashraf et al. 2009). The addition of Si to the hydroponic solution enhanced fruit firmness, total soluble solids and vitamin C content in tomato fruits (Liang et al. 1993; Stamatakis et al. 2003; Xue et al. 2012), while fertilization of strawberry with Si resulted in an increased tissue consistency and durability of fruits during post harvest (Babini et al. 2012). In apple, the application of Si increased the content of soluble solid and vitamin C and reduced the level of titratable acid in the fruit, but did not affect the fruit hardness (Su et al. 2011). Shi et al. (2010) found that Si applications increased the contents of total soluble solids, sugar and acids, but decreased the level of nitrate in grape. Wang et al. (2007) observed a yield increase in cucumber in the range of 5.1 to 10.2 %, depending on the application rate of Si. Liu et al. (2014) observed not only an increase in single cucumber fruit weight but also an improvement in cucumber quality. They found that the levels of sugar and vitamin C were significantly increased, while the level of NO$_3^-$-N was decreased. The role of Si in increasing sugar
concentration in the cucumber fruit is still unclear, but may be related to Si-promoted photosynthesis, as previously suggested (Li and Ma 2002). The decrease of NO$_3^-$-N level in cucumber may be due to Si-mediated increase in N use efficiency, as observed in rice (Detmann et al. 2012). Further study is needed to clarify the mechanisms for these Si-mediated changes in fruit quality.

In addition, supplementation of Si is reported to improve the flower quality traits of gerbera (Savvas et al. 2002; Kamenidou et al. 2010), zinnia (Kamenidou et al. 2010) and rose (Voogt and Sonneveld 2001) under greenhouse conditions.

References


References

Liu JM, Han C, Sheng XB, Liu SK, Qi X. Potassium-containing silicate fertilizer: its manufacturing technology and agronomic effects. Oral presentation at 5th International Conference on Silicon in Agriculture; September 13–18, Beijing; 2011.
Effect of Silicon on Crop Growth, Yield and Quality


References