High Yielding Performance of Soybean in Northern Xinjiang, China

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Abstract: The experimental site (Shihezi, Xinjiang, China) is located in an arid area of central Asia with abundant solar radiation of almost 10 daily sunshine hours from April to September. The yield potential in this area appears to be high if sufficient water is supplied. The yields of five soybean (Glycine max (L.) Merr.) cultivars including three semi-indeterminate Chinese cultivars (Shidadou 1, Xindadou 1 and Suinong 11) and two determinate Japanese cultivars (Toyomusume and Toyokomachi) were evaluated over three years. These cultivars were grown under drip irrigation, a high planting density (22.2 plants m⁻²) and heavy applications of farmyard manure (15 t ha⁻¹). Each cultivar showed a high leaf area index (LAI). In particular, the maximum LAI was greater than 7 over the three years in Shidadou 1 and Toyokomachi. The three Chinese cultivars with a high plant height had a low LAI in the upper layers of the canopy, but the two Japanese cultivars with a short plant height had a higher LAI in the middle or upper layers. Toyokomachi and Shidadou 1 had the highest seed yield, followed by Toyomusume. In particular, the seed yield of Toyokomachi was as high as 8.67 t ha⁻¹ on the average of the three years. These high-yielding cultivars had more than 60 pods per plant (1350 m⁻²). The high yields in this experiment could be due to the large amount of intercepted radiation owing to the high LAI and abundant solar radiation, frequent and sufficient irrigation by the drip irrigation, and large number of pods as a sink.

Key words: Abundant solar radiation, Drip irrigation, Glycine max (L.) Merr., Leaf area index, Pod number, Xinjiang, Yield.

Shihezi, where the experiment was conducted, is located in northern Xinjiang, China. This is an arid area of central Asia with abundant solar radiation of almost 10 daily sunshine hours from Apr. to Sept. The availability of solar radiation defines the maximal limit in crop yield because intercepted solar radiation provides the energy for photosynthetic CO₂ fixation (Sinclair, 1994). On the other hand, water from melting ice in the Tianshan Mountains provides irrigation plentifully during the growing season, although the average precipitation per year is only about 200 mm. A water-saving irrigation system, drip irrigation, has been progressively adopted in this area. The drip irrigation system has several advantages such as controlled application, maintenance of a high soil-water potential in the root zone, partial soil wetting and the maintenance of dry foliage (Dasberg and Or, 1999). In addition, there is little damage by insects, diseases and weeds due to severe coldness in winter and dryness in summer. We recorded a soybean seed yield of 5.4 t ha⁻¹ using furrow irrigation in this area (Wang et al., 1995). The yield potential in this area appears to be high if sufficient water is supplied by an appropriate method such as drip irrigation. In this experiment, we estimated the yield potential of soybeans in this area grown under drip irrigation using cultivars with different stem habits.

Materials and Methods

The experiment was conducted in an experimental field of the Shihezi Agricultural and Environmental Institute for Arid Areas in Central Asia, Shihezi, Xinjiang, China (long. 86°02'E, lat. 44°18’N) in 2002, 2003 and 2004. The soil texture of the field is light clay with the components shown in Table 1. The experimental plots were arranged in a split plot design with three replications. Year and cultivar were used as the main and sub-plot factors, respectively. Each plot was 5.4 m × 21.0 m in size. Five cultivars of soybean (Glycine max (L.) Merr.) were grown over the three years. Shidadou 1, Xindadou 1 and Suinong 11 are semi-indeterminate Chinese cultivars. The former two cultivars were bred in Xinjiang and the last one in Heilongjiang. Toyomusume and Toyokomachi are determinate Japanese cultivars which were bred at Hokkaido Prefectural Tokachi Agricultural Experimental Station (Memuro, Tokachi, Hokkaido, Japan).

Seeds were sown at a density of 22.2 plants m⁻² on 8 May 2002, 5 May 2003, and 29 Apr. 2004. Two alternate unequal row spacings, 30 cm and 60 cm, with 10 cm intra-row spacing were adopted, and irrigation
was applied using a drip method. Drip tapes with emitters at 20-cm intervals were used in the narrow row spacings. The total amounts of precipitation and irrigation during the growing period were 445, 363 and 465 mm in 2002, 2003 and 2004, respectively (Table 2). Farmyard manure (FYM; 15 t ha$^{-1}$), which was made from fowl droppings containing N, P$_2$O$_5$ and K$_2$O at rates of 240, 300 and 195 kg ha$^{-1}$ with a C/N ratio of 7.9, and a porous soil conditioner made from coal ash (375 kg ha$^{-1}$, about 5 mm diameter) were applied in autumn of the previous year. The same amounts of FYM, the soil conditioner and no chemical fertilizer were applied every year from 2000 in this field. The crop rotation of this field was cotton – industrial tomato – soybean. No pest or insect control was undertaken because there was little crop damage. After emergence, complementary transplanting was carried out in the missing stands.

Fourteen plants from each replication were sampled at 14 d intervals from 20 June to 20 Aug. in 2002, from 20 June to 29 Aug. in 2003, and from 16 June to 25 Aug. in 2004. The dry weights of roots, stems plus petioles, leaves and pods from 10 plants, excluding two extremely large and two small plants, were measured after oven drying for 48 h at 80°C. Leaf area was measured with an automatic area meter (AAM-7, Hayashidenko Inc., Japan). At the same time, pod and node numbers on the main stem and branches were recorded. The leaf area and dry weight in successive 10-cm layers from the top to the base (vertical distribution) were measured for six plants of each cultivar on 29 July, 2002. Radiation interception was measured on 26 and 27 July, 2002, with simple integrated solarimeter films (10 mm × 35 mm, 60 mg, Optleaf, Taisei E & I Inc., Japan; Yoshimura et al., 1990). After sunset on 25 July, 30 simple integrated
solarimeter films were stuck on the leaflet surface in each 10-cm layer of each cultivar using double-sided binding tape, and they were detached from the leaflets at night after two days. The percentage of dye feeding was measured with a spectrophotometer (U-1000, Hitachi Corp., Japan) before and after the experiment. The radiation intercepted by the films was estimated from dye fading, and the intercepted radiation per unit leaf area was calculated (Isoda et al., 1992). Similar measurements for vertical distribution of leaf area, dry weights and radiation interception were conducted in 2003 and 2004 (data not shown because they are similar to those in 2002).

Seed yield and yield components of 19 plants (34 plants in 2004) in each plot, excluding two extremely large and two small plants, were examined from 22 Aug. to 13 Sept. in 2002, from 16 Aug. to 11 Sept. in 2003, and from 17 Aug. to 8 Sept. in 2004. Pod and seed numbers were counted and only matured seeds were weighed after complete air-drying. Harvest index was calculated as a ratio of seed yield at harvest divided by the sum of leaf, stem and root dry weights at the maximum growth stage and seed yield at harvest.

### Results

#### 1. Climatic conditions in Shihezi

Fig. 1 shows the meteorological data of the experimental years in Shihezi, in comparison with those in Memuro, Tokachi, Japan at a similar latitude (42°54’N), where Toyokomachi and Toyomusume were bred. The mean air temperature in Shihezi was much higher than that in Memuro during the growing season, in addition to very low precipitation. In particular, the sunshine hours in Shihezi were 2-3 times longer than in Memuro. In 2002, the sunshine hours were shorter in Apr. with much rain and low air temperature. The sunshine hours in 2004 were 150 h longer than in 2002 and 2003 during the period from Apr. to Sept.

#### 2. Branch, node and pod numbers

Table 3 shows the mean values of branch, node and pod numbers per plant as an average of the three years. The two Japanese and three Chinese cultivars had quite different numbers of branches and podding sites (main stem or branches) because of their different stem determination habits. The Japanese cultivars, Toyomusume and Toyokomachi, had more branches than the three Chinese cultivars, Shidadou 1, Xindadou 1 and Suinong 11, but the number of nodes on the main stem was only about a half that of the Chinese cultivars. The Chinese cultivars had a large number of pods on the main stem, but few on the branches. However, the two Japanese cultivars had many pods on the branches. The total pod number was greatest in Shidadou 1, followed by Toyokomachi and Toyomusume. Suinong 11 had the least pods.

#### 3. Leaf area index

In 2002, every cultivar rapidly increased its leaf area index (LAI) from late June to early July (Fig. 2). In particular, Shidadou 1 attained the largest LAI (9.3) at the end of July, and maintained a relatively high LAI until the end of Aug. The other cultivars also showed a high LAI (> 6). In 2003, increasing rates of LAI were low compared with those in 2002 because of cooler air temperatures in early July. Toyokomachi showed the highest LAI at the middle of July, followed by Shidadou 1. The LAI of Suinong 11 was lower during almost the entire growing period. In all cultivars in 2003, especially Toyokomachi and Shidadou 1, LAI was kept high for a longer period, until the end of the season, as compared with those in 2002. In 2004, in the Japanese cultivars LAI increased rapidly in June, and was kept high until the end of Aug. Shidadou 1 and Suinong 11 attained their maximum LAIs in the middle of Aug., with rather high values. Xindadou 1 showed lower LAIs when compared with the other Chinese cultivars.

### Table 3. Numbers of branches, nodes and pods per plant of the three years.

| Cultivar          | Branch number | Node number | Pod number |
|-------------------|---------------|-------------|------------|
|                   |               | Main stem   | Branche    | Total      | Main stem | Branche    | Total      |
| Shidadou 1        | 1.71b         | 19.8a       | 13.9ab     | 33.7ab     | 53.1a     | 15.7b      | 68.8a      |
| Xindadou 1        | 2.24b         | 16.8b       | 11.7b      | 28.5b      | 35.7b     | 15.9b      | 51.6bc     |
| Suinong 11        | 2.20b         | 20.2a       | 17.5ab     | 37.8a      | 32.8b     | 14.7b      | 47.5c      |
| Toyomusume        | 6.76a         | 9.8c        | 18.4ab     | 28.2b      | 19.2c     | 37.5a      | 56.7abc    |
| Toyokomachi       | 7.55a         | 9.6c        | 20.7a      | 30.2ab     | 19.9c     | 44.0a      | 63.9abc    |

Significance

- Year: ***, **, *** : 5, 1 and 0.1 % level of significance, respectively.
- Cultivar: *** : 0.1 % level of significance.
- Year x Cultivar: *** : 0.1 % level of significance.

Mean values followed by the same letter are not significantly different at 5 % level by Fisher’s LSD.
Canopy structure and radiation interception

Canopy structures late in July were quite different between the Chinese and Japanese cultivars, mainly due to the different stem determination types (Fig. 3). The three Chinese cultivars, especially Shidadou 1 and Suinong 11, with a high plant height, showed a low LAI in the upper layers. In Shidadou 1 and Suinong 11, the dry weight of pod was lighter than in the other 3 cultivars (Fig.3), due to their later maturity. Toyokomachi with a short plant height had a higher LAI in the middle layers, while Toyomusume had the highest LAI at the third layer from the top of the canopy.

In the Chinese cultivars, the amount of intercepted radiation per unit leaf area (IRL) tended to be larger in the upper layers, and it was intercepted less than 1 MJ m\(^{-2}\) d\(^{-1}\) in the layers below 80, 50 and 60 cm in Shidadou 1, Xindadou 1 and Suinong 11, respectively (Fig. 4). Toyokomachi showed a higher IRL in every layer compared with Toyomusume, despite having a larger leaf area in the middle and upper layers.

Yield and yield components

Table 4 shows days from emergence to the maturity, yield and yield components in each year. Toyokomachi and Toyomusume matured earlier than the Chinese cultivars. Shidadou 1 matured the latest, about 30 d later than the Japanese cultivars. Shidadou 1 and Toyokomachi had a larger number of pods; it was higher than 1350 m\(^{-2}\) in all three years. The pod number significantly differed among years, and was lower in 2003 than in 2004. However, the seed number per pod was not significantly different among the years. The Chinese cultivars tended to have a larger number of seeds per pod compared with the Japanese cultivar, and Suinong 11 had the largest number of seeds per pod (3.07). Toyokomachi had the heaviest 100 seed weight, followed by Toyomusume, and the Chinese cultivars had a lighter seed weight than the Japanese cultivars. There were significant differences in the seed number per pod and 100 seed weight both among years and in the interaction of year × cultivar. Toyokomachi and Shidadou 1 had very high seed yields, followed by Toyomusume. In particular, Toyokomachi recorded more than 800 g m\(^{-2}\) (8 t ha\(^{-1}\)) in all three years. The seed yield significantly varied with the year and was lower in 2003 than in 2004. The Japanese cultivars tended to have a higher harvest index than the Chinese cultivars.

Discussion

The seed yield of soybean, in particular that of Toyokomachi, was very high in this experiment. The availability of solar radiation defines the maximal limit of crop yield (Sinclair, 1994). In the present study, the daily sunshine hours during the growing season were as long as almost 10 hours. The LAI of the cultivars used was also high due to relatively high air temperature in May and June. In most of the cultivars used, the maximum value of LAI was higher than 6 in all three years. This value is similar to that estimated by Nakaseko et al. (1984) as required for 5-6t ha\(^{-1}\) of seed yield. Thus, the amount of intercepted radiation, which is a product of solar radiation and LAI, was large in this experiment, and this may be one of the main reasons for the high yield. However, a high LAI often causes reduction in dry matter production under
low-intensity light conditions. Soybean plants have been considered to intercept radiation less effectively because of the dense leaves in the upper layers of the canopy (Shaw and Weber, 1967; Johnston et al., 1969; Blad and Baker, 1972; Isoda et al., 1992). This is especially the case at high planting densities. The Japanese cultivars used in this experiment had short stems and a large LAI of about 8 having dense leaves in the canopy. However, IRL values in the upper three layers (30 cm) were higher in Toyokomachi than in Toyomusume, because the canopy structure of Toyokomachi was an ellipse type, not a table type. The ellipse-type canopy had the largest leaf area in the middle layers, mutual shading due to a dense leaves might not be serious compared with a table-type canopy; In addition, abundant solar radiation was available during the growing season in the present experiment conducted in northern Xinjiang. Black (1963) and Nakaseko and Gotoh (1981) reported that the optimum LAIs and the maximum crop growth rates increased with increasing solar radiation in subterranean clover and kidney bean, respectively. Such abundant incoming radiation might reduce mutual shading and increase radiation penetration into the canopy.

The possible reasons for the high yields in this experiment besides abundant solar radiation and high LAI are as follows. The first is that water could be more effectively applied to meet plant needs by the drip method.
irrigation system used in this experiment than with other irrigation systems or rain-fed cultivation because of the higher degree of control of water application (Dasberg and Or, 1999). Secondly, heavy applications of FYM could be a reason for the high seed yields. Olsen (1986) pointed out that plants fertilized with FYM were able to utilize nitrogen more efficiently and conserve energy for growth, since FYM provides a steady supply of NH₄⁺ during the growth period. The steady supply of nitrogen might support photosynthesis and the translocation of nitrogen to seeds throughout the growing season, especially at the grain-filling period. In addition, the soil structure might also be improved by the application of FYM (Avnimelech, 1986).

Whigham (1983) listed the world record of soybean yield as 7.4 t ha⁻¹. Several high yielding records have also been reported by Gotoh (1982). According to his report, the highest yield, 7.86 t ha⁻¹, was recorded in a field of the Miyagi Prefectural Agriculture Station, Japan, in 1960. He surmised from these records that 1300 – 1400 pods m⁻², 1.8 seeds per pod, and 25 g per 100 seeds are required to attain a seed yield of 6 t ha⁻¹. Toyokomachi, which recorded the highest yield in this experiment, had 1360 pods m⁻², 2.18 seeds per pod, and 27.5 g per 100 seeds (the average of the three years). This satisfies the conditions listed by Gotoh (1982).

Kokubun (1988) noted that the seed yield increased with increasing planting density in the varieties that had no branches. Donald and Hamblin (1983) also proposed that the non-branching habit is a principal characteristic of the ideotype for all annual seed crops. However, in this experiment, Toyokomachi had about 7.5 branches per plant (about 30 nodes per plant), and produced more than 1350 pods per m⁻². Toyokomachi was released by the Hokkaido Prefectural Tokachi Agricultural Experimental Station in 1988, and is now one of the leading cultivars in the Hokkaido area. Its average yield at the experimental station was 2.59 t ha⁻¹ having 4.5 branches per plant (Sasaki et al., 1990). Toyokomachi is not always an exceptionally high-yielding cultivar in its main cultivation area. Therefore, its high yield in this experiment might be a result of genotype x environment interaction. On the other hand, Shidadou 1, which was bred in Shihezi, Xinjiang, seems to have a few branches and many pods on the main stem, characteristics of the ideotype described by Donald and Hamblin (1983). Under favorable cultivation conditions, such as in this experiment, a cultivar that produces many pods per unit area and maintain a high LAI, could attain high yields regardless of its stem determination type. Specht et al. (1999) estimated that the yield limit of soybean would be 8 t ha⁻¹. The highest yield obtained in this experiment exceeded it. Although the yield in this

| Cultivar          | Seed number per pod | 100 Seed weight (g) | Seed yield (g m⁻²) | Harvest index (%) |
|-------------------|---------------------|--------------------|-------------------|-------------------|
| Shidadou 1        | 131                 | 126                | 1352a             | 1526a             |
| Xindadiou 1       | 107                 | 111                | 1157c             | 11352a            |
| Shidadou 1        | 123                 | 110                | 983c              | 1352a             |
| Xindadiou 1       | 123                 | 110                | 1175c             | 1352a             |
| Suinong 11        | 114                 | 125                | 1022c             | 11352a            |
| Xindadiou 1       | 114                 | 123                | 1175c             | 1352a             |
| Toyomusume        | 100                 | 106                | 983c              | 1352a             |
| Toyokomachi       | 98                  | 118                | 1350b             | 1352a             |

Table 4. Yield and yield components in 2002, 2003 and 2004.
experiment was estimated from the values obtained in small plots, we now intend to conduct yield trials on a large scale to confirm the yield potential of the soybean, and to analyze the reasons for high yielding in detail.

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