

Growth of High-Yielding Soybeans and its Relation to Air Temperature in Xinjiang, China

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Abstract: The growth and seed yields of 2 Japanese and 3 Chinese cultivars of soybeans cultivated in 2002-2005 using a drip irrigation system in the arid area of Xinjiang, China, were analyzed with respect to growth parameters and air temperature. Seed yield was very high in 2002, 2003 and 2004, but relatively low in 2005. The variation among years in seed yield clearly depended on pod number. The mean leaf area index (LAI) and crop growth rate (CGR) in 2005 was lower than those in the other 3 years. CGR showed significant positive correlations with mean LAI at the early growing stages, and with net assimilation rate (NAR) at the later growing stages. The increasing rate of pod number (IRP) was positively correlated with the mean LAI and CGR at the pod setting period, suggesting that an adequate supply of photosynthates would be required for pod setting. It was concluded that excellent growth in the years with high yields was supported by the large LAI before the pod setting periods and by high NAR and vigorous pod growth at the latter half of the growing season.

Key words: Air temperature, Arid areas, Drip irrigation, Growth parameters, Pod number, Soybean.

It is difficult to obtain a high yield in soybean in successive years due to its compensatory growth and alterations in plant development, though many attempts have been made to obtain a high yield (Nakaseko et al., 1984). We previously reported that the yield of soybean was very high in Xinjiang, China in 2002, 2003 and 2004 seasons (Isoda et al., 2006). In 2005, however, the seed yield was very low. Such a fluctuation in seed yield among years is influenced largely by climatic conditions, especially by air temperature (Hesketh et al., 1973; Huxley et al., 1976; Sato and Ikeda, 1979; Seddigh and Jolliff, 1984; Jiang and Egli, 1995; Gibson and Mullen, 1996; Uchikawa et al., 2003; Kitano et al., 2006). On the other hand, pod number is considered to be one of the main factors for determining seed yield, and the variation in seed yield was often explained by pod number (Ikeda and Sato, 1990; Shimada et al., 1990; Board and Harvill, 1994; Wang et al., 1995; Saitoh et al., 1998). A high night air temperature has been reported to increase pod number (Gibson and Mullen, 1996; Zheng et al., 2002), but to reduce seed yield (Huxley et al., 1976; Sato and Ikeda, 1979; Seddigh and Jolliff, 1984). In this experiment, therefore, we examined the differences in growth among years in terms of the effect of air temperature on the growth parameters and pod setting, and to assume the conditions necessary to obtain a high

yield in soybean in Xinjiang, China.

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, 2004 and 2005. 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 four years. Indeterminate Chinese cultivars Shidadou 1 and Xindadou 1 bred in Xinjiang and Suinong 11 bred in Heilongjiang, and determinate Japanese cultivars Toyomusume and Toyokomachi bred at Hokkaido Prefectural Tokachi Agricultural Experimental Station (Memuro, Tokachi, Hokkaido, Japan) were used. Seeds were sown at a density of 22.2 plants m⁻² on 8 May in 2002, 3 May in 2003, and 29 in Apr. 2004 and 2005. Two alternate unequal row spacings, 30 cm and 60 cm, with 10 cm in intra-row spacing were adopted, and irrigation was applied using a drip method. Drip tapes with emitters every 20 cm were set in the narrow row spacings. The amounts of precipitation and irrigation during the growing period were 445 mm,

Received 26 March 2009. Accepted 24 November 2009. Corresponding author: A. Isoda (isoda@faculty.chiba-u.jp, fax +81-47-308-8814).

Abbreviations: CGR, crop growth rate; IRP, increasing rate of pod number; LAI, leaf area index; MAT, mean air temperature; NAR, net assimilation rate; PGR, pod growth rate.

Table 1. Date of sampling and growing stages of soybeans.

Year	Sampling and growing stage**						
	0*	1	2	3	4	5	6
		R2	R4(R5)***	R5(R6)	R6(R7)	R7(R7~8)	R8
2002	15 May	20 June	9 July	23 July	6 Aug.	20 Aug.	3 Sept.
2003	12 May	21 June	4 July	19 July	2 Aug.	16 Aug.	30 Aug.
2004	13 May	16 June	30 June	14 July	28 July	11 Aug.	25 Aug.
2005	6 May	16 June	30 June	15 July	27 July	11 Aug.	—

*, Emergence. **, According to Fehr and Caviness (1977). ***, Shidadou 1 and Suinong 11 without parentheses, and Xindadou 1, Toyomusume and Toyokomachi in parentheses.

363 mm, 465 mm and 376 mm in 2002, 2003, 2004 and 2005, respectively. Farmyard manure (15 t ha⁻¹), which was made from fowl droppings and included N, P₂O₅ and K₂O at rates of 240, 300 and 195 kg ha⁻¹ with a C/N ratio of 7.9, and porous soil conditioner which was made from only coal ash (375 kg ha⁻¹, about 5 mm diameter) was applied in autumn of the previous year. The same amounts of farmyard manure and soil conditioner without chemical fertilizer were applied every year from 2000 in this field. The crop rotation of this field was cotton–industrial tomato–soybean in every tree year. 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 around 14 d intervals from 20 June to 20 Aug. in 2002, from 20 June to 29 Aug. in 2003, from 16 June to 25 Aug. in 2004, and from 16 June to 11 Aug. in 2005 (Table 1). The difference in growth at each stage among years was very few, because sampling was done earlier in the years for earlier seeding (2004 and 2005). The dry weights of roots, stems and petioles, leaves and pods from ten 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., Tokyo, Japan). Pod number was counted for the pods longer than about 2cm. Roots were dug up around 10 cm from the stem in circumference and 30 cm in depth. Mean leaf area index (LAI), crop growth rate (CGR), net assimilation rate (NAR), pod growth rate (PGR), increasing rate of leaf area index (Δ LAI) and increasing rate of pod number (IRP) were calculated as follows:

$$\text{Mean LAI} = (\text{LAI}_2 - \text{LAI}_1) / (\ln \text{LAI}_2 - \ln \text{LAI}_1)$$

$$\text{CGR} = (W_2 - W_1) / (t_2 - t_1)$$

$$\text{NAR} = \text{CGR} / \text{Mean LAI}$$

$$\text{PGR} = (W_{p_2} - W_{p_1}) / (t_2 - t_1)$$

$$\Delta \text{LAI} = (\text{LAI}_2 - \text{LAI}_1) / (t_2 - t_1)$$

$$\text{IRP} = (N_{p_2} - N_{p_1}) / (t_2 - t_1)$$

Where, LAI₁, W₁, W_{p1} and N_{p1}, and LAI₂, W₂, W_{p2} and N_{p2} indicate leaf area index, total dry weight, pod dry

weight and pod number per m² at t₁ and t₂, respectively.

Seed yield and yield components of 19 plants (34 plants in 2004 and 2005) for each plot, excluding two extremely large and two small plants, were examined in periods from 22 Aug. to 13 Sept. in 2002, from 16 Aug. to 11 Sept. in 2003, from 17 Aug. to 8 Sept. in 2004, and from 22 Aug. to 11 Sept. in 2005. Pod and matured seed numbers were counted and weighed after complete air-drying.

Results

1. Climatic conditions

Figure 1 shows the sunshine hours and mean air temperature (MAT) at each growth stage over 4 years. Sunshine hours in 2002 and 2003 were lower than those in 2004 and 2005. In particular, those from the Stage 2 to 5 in 2002 were low. On the contrary, those in 2004 and 2005 were higher in the first half, and lower in the second half of the season. Mean sunshine hours during the growing period were largest in 2004 (11.1 h), followed by 2005 (10.9 h) and 2003 (10.5 h). 2002 was the least (10.1h). MAT increased rapidly from Stage 0 to 2. MAT in 2005 was higher from Stage 1 to 3. Those in 2003 were lower during most of the growing periods. During the whole growing periods, however, there was no large difference in MAT, varying from 22.4°C in 2004 to 22.9°C in 2005. Fig. 2 indicates monthly amount of irrigation and precipitation. There was no large difference among years in total amount of irrigation and precipitation, though the amount of precipitation during the growing season was largest in 2004, and smallest in 2005. The sum of precipitation and irrigation ranged from 359.7 mm in 2002 to 434.5 mm in 2004.

2. Seed yield and pod number

Seed yields in 2005 were extremely lower than those in the other years (Table 2). In particular, Shidadou 1, Toyomusume and Toyokomachi had only about one of the half seed yields in 2002, 2003 and 2004. Pod number was very low in 2005. Toyokomachi, which showed the highest pod number in all years, though the number in 2005 was less than one half of that in 2004.

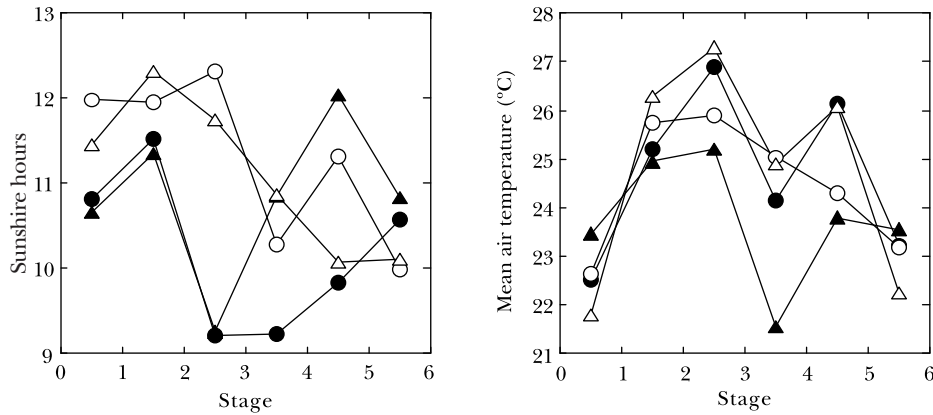


Fig. 1. Sunshine hours and mean air temperature at each stage over 4 years.
●, 2002; ▲, 2003; ○, 2004; △, 2005.

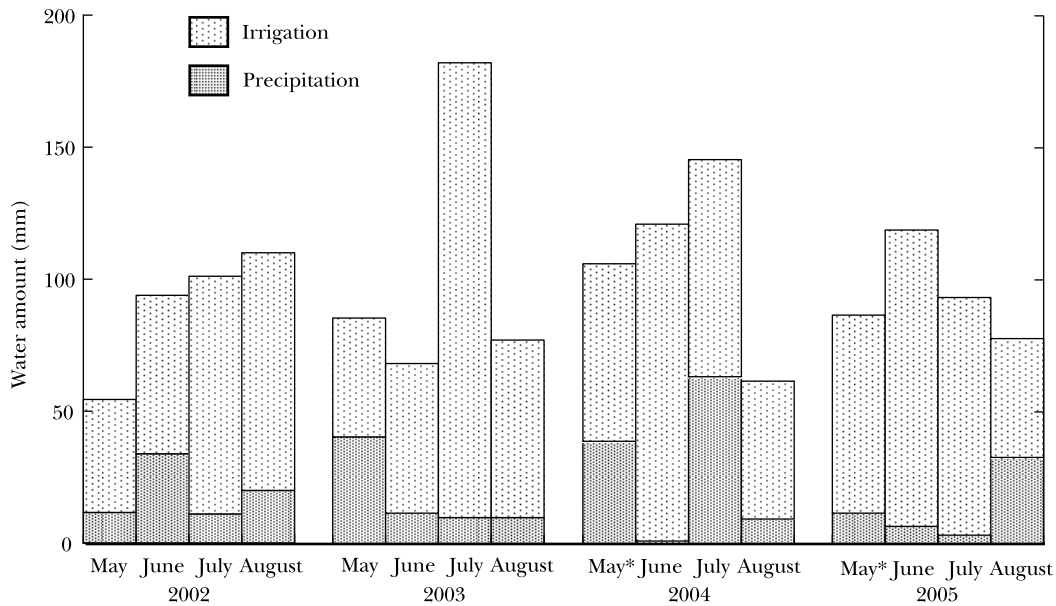


Fig. 2. Monthly amount of irrigation and precipitation.
*, including 30 mm irrigated at the end of April.

Table 2. Yield and yield components of soybeans over 4 years.

Cultivar	Growing days#				Pod number				Seed number				100 Seed weight				Seed yield			
	2002	2003	2004	2005	(m ⁻²)				per pod				(g)				(g m ⁻²)			
Year	2002	2003	2004	2005	2002	2003	2004	2005	2002	2003	2004	2005	2002	2003	2004	2005	2002	2003	2004	2005
Shidadou 1	131	126	115	130	1526a	1352a	1545ab	730ab	3.00b	2.70b	2.72ab	2.43b	17.1bc	20.7c	18.3b	21.0b	783.9a	758.0ab	743.3b	378.1a
Xindadou 1	107	111	107	114	1137c	854c	1271c	695abc	2.81c	2.77b	2.58b	2.49b	17.8b	18.3d	16.7b	21.1b	568.4b	434.0c	565.9c	402.4a
Suinong 11	114	123	110	126	1032c	883c	1154c	675bc	3.14a	3.25a	2.82a	2.73a	16.0c	17.4d	16.7b	19.2b	518.7b	501.0c	543.8c	381.1a
Toyomusume	100	106	106	109	1335b	1143b	1373bc	648c	2.12d	2.25c	2.09c	1.84c	27.3a	25.6b	26.0a	28.8a	771.7a	655.4b	743.4b	382.7a
Toyokomachi	98	118	98	121	1350b	1370a	1642a	761a	2.19d	2.11c	2.23c	1.94c	28.4a	29.0a	25.1a	29.1a	841.0a	838.5a	920.0a	436.0a
Significance																				
Year	—				***				***				***				***			
Cultivar	—				***				***				***				***			
Year × Cultivar	—				***				***				***				***			

***, 0.01% level of significance. Mean values followed by the same letter are not significantly different at 5% level by Tukey's test. #, Days from the emergence to the leaf yellowing day.

Fig. 3 shows the relationship between seed yield and pod number over 4 years, showing a close positive correlation. The variation among years in seed yield depended clearly on pod number, and all cultivars showed the same tendency. Fig. 4 shows changes with time in pod number. All cultivars except Xindadou 1 and Suinong 11 had fewer pods in 2005 than in the other years. Shidadou 1 had the largest number of pods among the cultivars except in 2005. Suinong 11 had fewer pods. The pod number in Xindadou 1, Toyomusume and Toyokomachi increased until Stage 3 except in 2004. Shidadou 1 and Suinong 11,

which had later pod formation as compared with the other cultivars, reached a plateau at Stage 4 except in 2004. Pod number for Shidadou 1, Xindadou 1 and Suinong 11 in 2004 increased until Stage 5. There was a tendency besides 2004 that the pod number in the Chinese cultivars increased until Stage 4, while that in the Japanese cultivars was almost determined by Stage 3.

3. Growth parameters

Fig. 5 shows the mean LAI over 4 years. Shidadou 1, which matured later than the other cultivars, showed the highest LAI, followed by Toyokomachi. Xindadou 1 tended to have low LAIs. In all cultivars, the mean LAI in 2005 was very low during the growing season. On the contrary, the LAI in 2002 was high, and it was higher than 9 in Shidadou 1. Only Suinong 11 had the largest LAI in 2004.

In general, CGR in 2005 was lower throughout the season in all cultivars (Fig. 6). All cultivars showed a low CGR at Stage 0 to 2 in 2005 except Shidadou 1. CGR in 2004 tended to be maintained higher at the later season in all cultivars. NAR was highest at Stage 0–1 of 2002 were highest for every cultivar except Shidadou 1 and Suinong 11, and decreased rapidly at the later stages. On the contrary, NAR in 2005 were lower as compared with the other years. During the growing season, there was a tendency to be higher in 2004. PGR had a peak at Stage 3–5 in all cultivars and years except 2002. In 2002, PGR in all cultivars showed increases in the earlier stages, and decreased earlier as compared with the other years. On average, PGRs were higher in 2004 than in the other years.

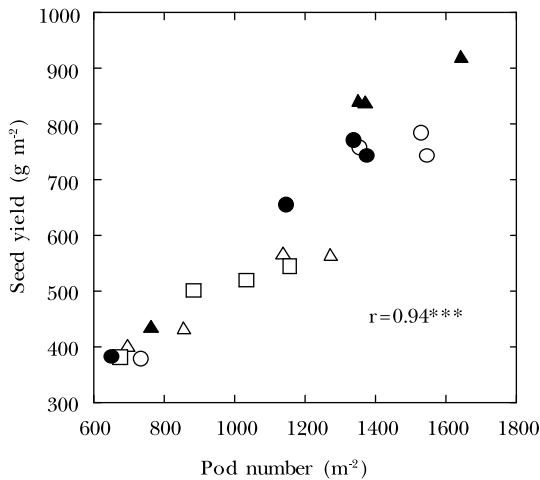


Fig. 3. Relationship between seed yield and pod number in soybeans at harvest over 4 years. ○, Shidadou 1; △, Xindadou 1; □, Suinong 11; ●, Toyomusume; ▲, Toyokomachi. *** indicates 0.1 % level of significance.

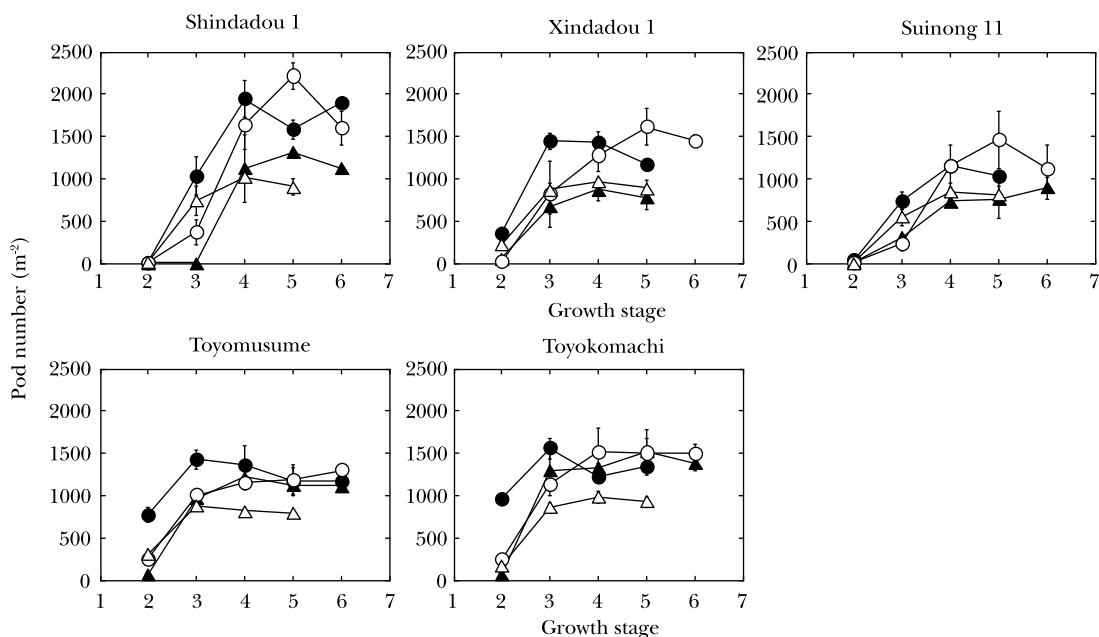


Fig. 4. Changes with time in pod number in soybeans over 4 years. Bars indicate standard errors of three replications at 5% level of probability. ●, 2002; ▲, 2003; ○, 2004; △, 2005.

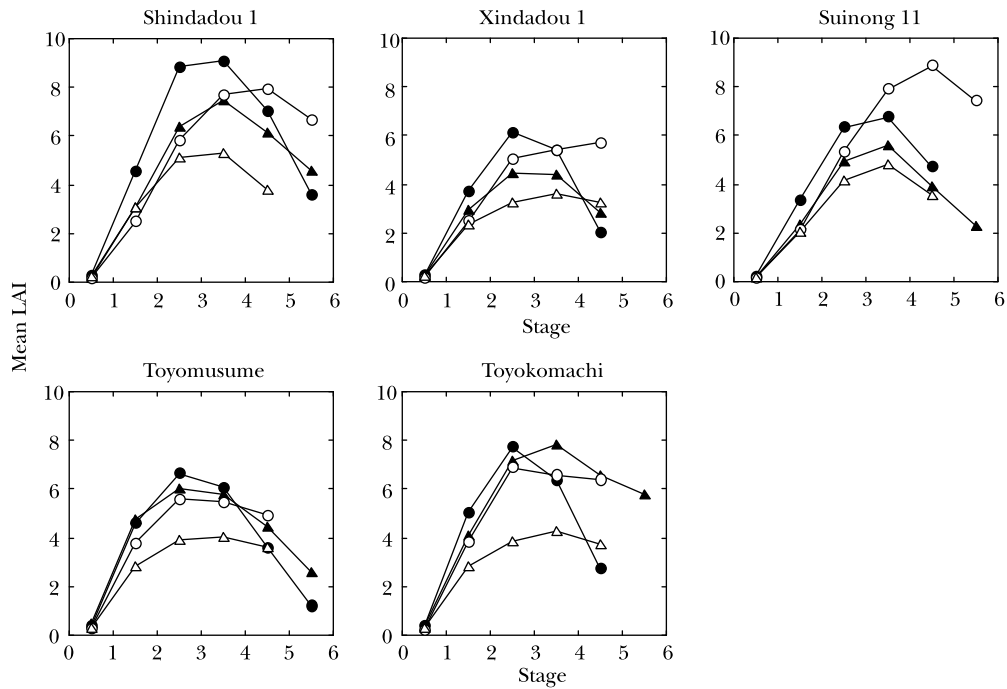


Fig. 5. Changes with time in mean leaf area index (mean LAI) in soybeans over 4 years. ●, 2002; ▲, 2003; ○, 2004; △, 2005.

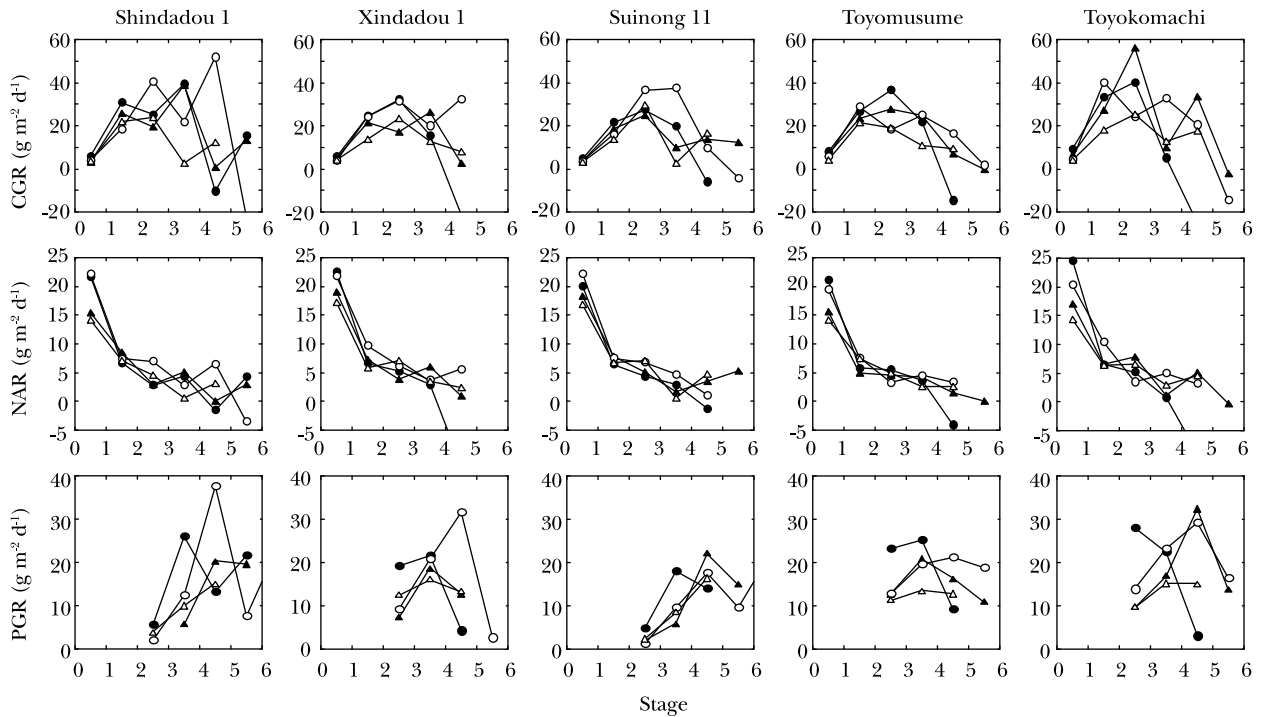


Fig. 6. Changes with time in crop growth rate (CGR), net assimilation rate (NAR) and pod growth rate (PGR) of soybeans over 4 years. ●, 2002; ▲, 2003; ○, 2004; △, 2005.

CGR showed a significant positive correlation with the mean LAI from Stage 1 to 2, indicating that a large LAI accelerated crop growth in these periods (Table 3). There was a close positive correlation between CGR and NAR at Stage 2–5. The mean LAI also had a positive correlation

with CGR at Stage 3–5.

4. Relations of IRP to growth parameters and effects of MAT on LAI, IRP and pod number

Fig. 7 shows the relations of IRP to CGR, mean LAI and

Table 3. Correlation coefficients among growth parameters at each stage of soybeans.

Stage ¹	CGR-Mean LAI	CGR-NAR	Mean LAI-NAR	CGR-PGR	PGR-Mean LAI	PGR-NAR
0-1	0.84**	0.41	-0.13	-	-	-
1-2	0.75**	0.38	-0.31	-	-	-
2-3	0.4	0.65**	-0.39	0.15	0.32	-0.14
3-4	0.56**	0.87**	0.12	0.21	0.1	0.27
4-5	0.51*	0.90**	0.43	0.91**	0.68**	0.77**
5-6	-0.66	0.95**	-0.74	0.70*	-0.48	0.80**

¹see Table 1. CGR, Mean LAI, NAR and PGR indicate crop growth rate, mean leaf area index, net assimilation rate and pod growth rate, respectively. * and ** indicate 5 and 1% level of significance, respectively. n=20.

NAR at Stage 2-3 and 3-4, when pod number increased greatly. At Stage 2-3, there was a positive correlation between IRP and mean LAI. In particular, IRP in Xindadou 1 had a very close relation to mean LAI. There was also a positive correlation between IRP and CGR, and IRP and mean LAI at Stage 3-4. IRP had no marked relationship with NAR at both stages.

Fig. 8 shows relationships between increasing rates of leaf area index (Δ LAI) and MAT at each stage. At Stage 0-1, Δ LAI were lower in 2005 when MAT was the lowest among years (21.8°C). Suinong 11 showed the lowest Δ LAI in all years. Although Toyomusume tended to increase Δ LAI with increasing MAT, there was no marked relationship between them in the other cultivars. On the contrary, in 2005 when MAT was the highest among the years (26.3°C), all cultivars in 2005 showed a lower Δ LAI at Stage 1-2. Shidado 1 tended to decrease Δ LAI with increasing MAT, while the other cultivars did not show such a tendency. At Stage 2-3 there was no clear relationship between Δ LAI and MAT. The Japanese cultivars tended to decrease Δ LAI with decreasing MAT at Stage 3-4, while the Chinese cultivars had no such tendency. There was no clear relationship between Δ LAI and MAT at Stage 4-5. Fig. 9 shows effects of MAT on the pod number at Stage 4 and IRP at Stage 2-3 and 3-4 when pod number was almost determined. Every cultivar had peaks of pod number at around 22.5°C, 25-26°C and 25.5-27°C at Stage 0-1, 1-2 and 2-3, respectively. At Stage 3-4, there was no peak due to lower pod numbers in 2005. IRP at Stage 2-3 for the Japanese cultivars showed significant negative correlations with MAT ($r=-0.98^{**}$ for Toyomusume and $r=-0.95^{**}$ for Toyokomachi), while there was no marked relation for the Chinese cultivars. At Stage 3-4, the Japanese cultivars and Xindadou 1 did not increase their pod number. MAT also did not affect IRP for Shindadou 1 and Suinong 11.

Discussion

One of the essential conditions for obtaining a high yield of soybean in this experiment was assumed to be a high LAI, near 8. The optimum LAI in soybean has been assumed to be about 4.5-6 (Ojima and Fukui, 1966;

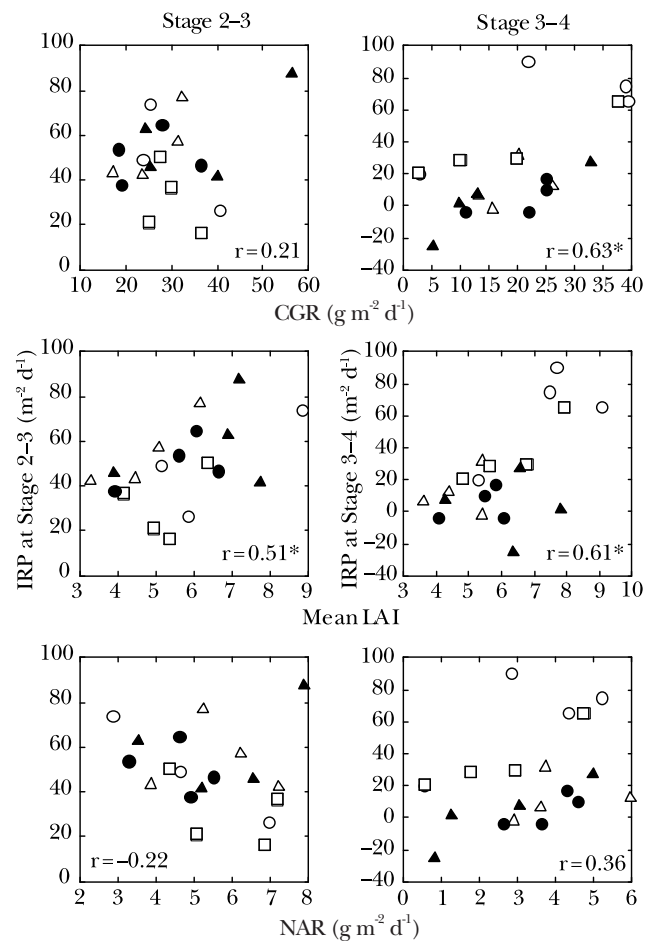


Fig. 7. Relations of increasing rate of pod number (IRP) with crop growth rate (CGR), mean leaf area index (LAI) and net assimilation rate (NAR) in soybeans at Stage 2-3 and 3-4.

○, Shidadou 1; △, Xindadou 1; □, Suinong 11; ●, Toyomusume; ▲, Toyokomachi. * indicates 5% level of significance.

Nakaseko and Gotoh, 1981b). On the other hand, Nakaseko et al. (1984) and Shimada et al. (1990) argued that an LAI of 6 to 8 would be needed to yield more than 5 t ha⁻¹ seed. In the present experiment, the maximum LAI in Toyokomachi was similar to that in the previous estimation, with higher yields. Soybean is said to have an ineffective canopy structure for radiation interception and

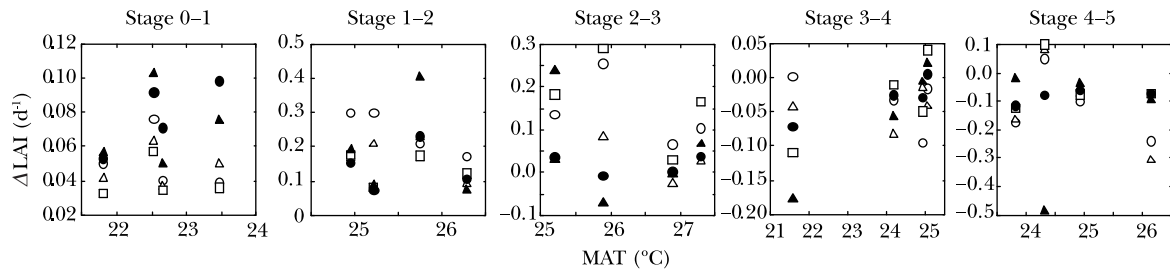


Fig. 8. Relations of increasing rate of leaf area index (Δ LAI) of soybeans with mean air temperature (MAT) at each stage. \circ , Shidadou 1; \triangle , Xindadou 1; \square , Suinong 11; \bullet , Toyomusume; \blacktriangle , Toyokomachi.

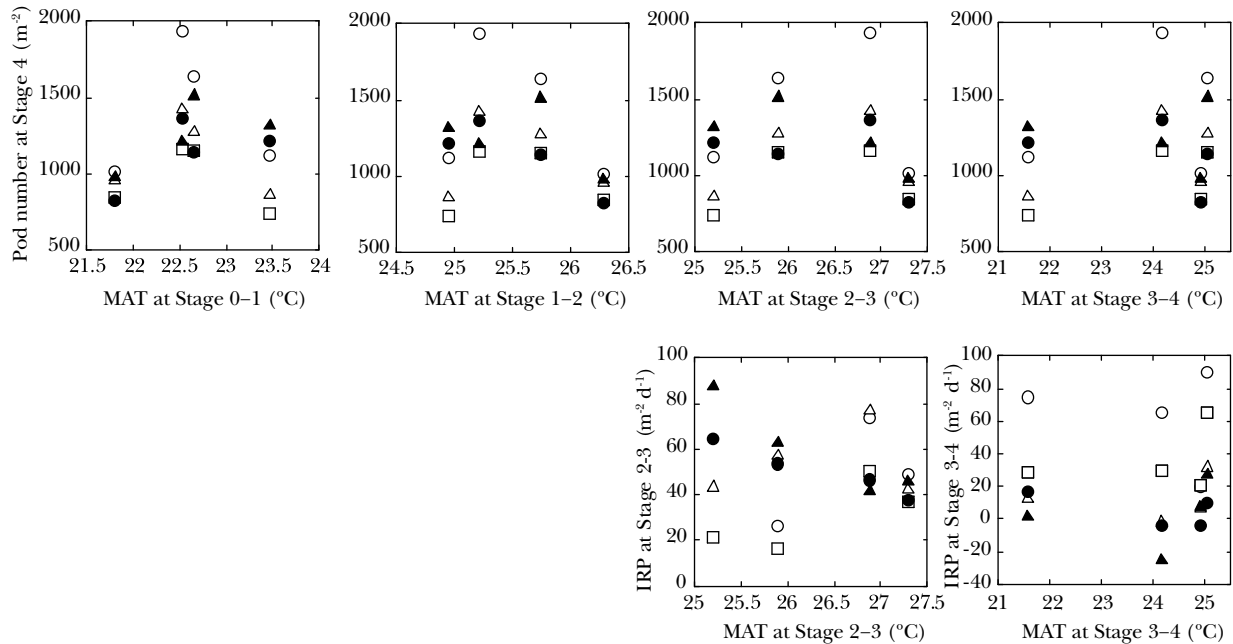


Fig. 9. Effect of mean air temperature (MAT) on pod number at Stage 4 and increasing rate of pod number (IRP) in soybeans. \circ , Shidadou 1; \triangle , Xindadou 1; \square , Suinong 11; \bullet , Toyomusume; \blacktriangle , Toyokomachi.

penetration (Johnston et al., 1969; Blad and Baker, 1972; Kokubun, 1988; Isoda et al., 1992). This tendency becomes worse particularly in a dense planting population, since radiation was intercepted by only upper layers of the canopy (Sakamoto and Shaw, 1967; Kumura, 1969; Isoda et al., 1993). In the present experiment, however, there was no significant relationship between NAR and mean LAI in any cultivars, demonstrating no severe mutual shading even at a higher LAI. We previously reported that Toyokomachi, which had the highest seed yield, had effective characteristics for radiation interception in spite of relatively large LAI (Isoda et al., 2006). In addition, abundant and intensive solar radiation might reduce mutual shading even at a range of large LAI as previously reported (Black, 1963; Nakaseko and Gotoh, 1981a). These conditions might therefore make it possible to have a large LAI without severe mutual shading.

In 2005, when a large LAI was not established, MAT at Stage 0–1 (emergence to middle of June) was lower and

that at Stage 1–3 was higher than in other years. Hofstra (1972) reported that leaf area reached a maximum at 30–27°C of day temperature. Sato (1976) also showed the peak of leaf expansion at 30°C and 25°C of the day and night temperatures, respectively. The low air temperature in 2005 might therefore restrict leaf expansion at Stage 0–1. At Stage 1–3, however, there was no clear relationship between air temperature and leaf area expansion, although high air temperatures in 2005 did not tend to accelerate leaf area extension. It was therefore suggested that other factors besides air temperature such as timing of water supply might limit leaf expansion at these stages. Kato (1964) reported that soybean differentiated flower buds 25 days before flowering. The low temperature from emergence to flowering in 2005 might therefore reduce flower number and pods set. On the other hand, it was also reported that seed number would be reduced if CGR decreased during the flowering and pod setting periods (Jiang and Egli, 1995). Board and Tan (1995) also

empathized that assimilatory capacity (source strength) from R1 to 10 to 12 d after R5 restricted pod number and yield. In the present experiment, the CGRs in 2005 were lower during these periods, mainly due to lower LAIs. Shortage of photosynthate supply might abort pods and consequently reduce seed yield in 2005 even though radiation and/or air temperature after the pod setting period were suitable. This is supported by the positive relations of IRP to CGR and mean LAI at the pod setting periods (Fig. 7).

As in previous reports (Kokubun 1988; Ikeda and Sato, 1990; Shimada et al., 1990; Wang et al., 1995; Saitoh et al., 1998; Board and Modali, 2005), the variation in seed yield in this experiment could be explained by pod number (Fig. 3), which was affected positively by mean LAI from the beginning of seed filling to the beginning of seed development and by CGR from the beginning of seed development to full seed maturation stage (Fig. 7). The high air temperature also tended to decrease IRP especially in the Japanese cultivars at Stage 2–3 (Fig. 9). There are several reports showing the relationship between pod setting and temperature. Uchikawa et al. (2003) analyzed the data of field experiments for 15 years, and showed that the optimum air temperature for seed number per m² was around 25°C. Under controlled conditions, Gibson and Mullen (1996) and Zheng et al. (2002) found that high night temperature increased pod and seed number but reduced seed size with no effect on seed yield. Kitano et al. (2006) also showed that high temperature treatment at the 14th to 18th day before the beginning of flowering increased the number of floral buds but reduced pod setting ratio. In 2005, therefore, the pod number might be reduced by the low air temperature in the early growing stage, but not by the high air temperature at the pod setting periods directly. On the contrary, Saitoh et al. (1998) found that the number of pods was closely correlated with the total number of floral buds but not with pods set. A high night temperature reduces seed yield (Huxley et al., 1976; Sato and Ikeda, 1979; Seddigh and Jolliff, 1984). Therefore, further research is required to determine the effects of air temperature on floral bud differentiation and pod setting as a limiting factor of seed yield in Xinjiang.

Acknowledgements

This series of research was inspired partly by the late Professor of Hokkaido University, Kimio Nakaseko. We are deeply grateful for his encouragement and guidance.

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