

## Effects of Water Table on Physiological Traits and Yield of Soybean

### II. Effects of water table and rainfall on leaf water potential and photosynthesis\*

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**Abstract :** The effects of constant and fluctuating water tables at 15–100 cm below the soil surface on the leaf water potential, stomatal conductance and photosynthesis of lysimeter-grown soybean (*Glycine max* cv. Ta-chinagaha) were examined during 1991 (wet year) and 1992 (dry year) in Tsukuba, and during 1992 in Fukuyama. The effects varied greatly with the amount of rainfall. During the wet year in Tsukuba, the apparent photosynthetic rate did not change while the stomatal conductance and leaf water potential decreased with the increasing depth of the water table in dry soil. In contrast, the apparent photosynthetic rate and water potential increased with the increasing depth of the water table in wet soil. During the dry year, the photosynthetic rate and stomatal conductance were highest when the water table was 40 cm below the soil surface. The leaf water potential decreased with the increasing depth of the water table both in Tsukuba and Fukuyama. These results suggest that the water table level affects the photosynthesis and water status of soybean leaves, the magnitude of the effect being dependent on the amount of rainfall.

**Key words :** Leaf water potential, Photosynthesis, Soybean, Stomatal conductance, Water table.

地下水位がダイズの生理機能と収量に及ぼす影響 第2報 地下水位および降雨条件が個葉の水ポテンシャル、光合成に及ぼす影響: 島田信二・国分牧衛・松井重雄\*\*\*\* (農業研究センター・\*\*\*\*中国農業試験場)

要旨: 地下水位の高低 (15–100 cm一定あるいは変動, 無灌水) がダイズ個葉 (主茎上位の活動中心葉) のみかけの光合成速度, 気孔コンダクタンス, 水ポテンシャルに及ぼす影響を明らかにするために, ライシメータを用いて茨城県つくば市 (1991年: 多雨, 1992年: 少雨), および広島県福山市 (1992年) において調査した。その結果, 降雨条件によって地下水位処理による影響が異なった。すなわち, 降水量が多かった1991年 (つくば市) では, 長期間にわたって降雨がなく土壌が乾いた状態では, 地下水位が高い区ほど水ポテンシャル, 気孔コンダクタンスが高かったが, みかけの光合成速度に処理間差はみられなかった。一方, 降雨後で土壌が湿った状態では, みかけの光合成速度, 葉の水ポテンシャルは, 地下水位が低いほど高かった。降水量が少なかった1992年は, つくば市と福山市ともに地下水位が40 cmの時に光合成速度, 気孔コンダクタンスとも最も高かった。また, 葉の水ポテンシャルは全般に地下水位が低いとやや低下する傾向がみられた。以上の結果は, 地下水位はダイズ個葉の光合成速度, 水分生理に大きな影響を与えること, およびその影響は降雨状況で異なることを示している。

キーワード: 気孔コンダクタンス, 光合成, ダイズ, 地下水位, 葉の水ポテンシャル。

Irrigation is an important cultural practice for soybean, not only in upland fields<sup>15)</sup> but also in drained paddy fields<sup>13,20)</sup> for obtaining higher yield. Some researchers have reported that high soybean yields were obtained where a water table was maintained at about 40 cm to 50 cm below the soil surface<sup>6,12,21,23)</sup>. The depth of the water table can be controlled in

general-purpose paddy fields by irrigation and drainage management. Previously, we examined that the effects of water table on leaf chlorophyll content, root growth and yield of soybean grown on a lysimeter<sup>24)</sup>, and showed that soybean productivity was much affected by water table depth and rainfall. Information on water table effects on soybean photosynthesis is very limited. Only Takeshima<sup>30)</sup> reported the effects of water table on photosynthesis of soybean plants. However, he used pot-grown plants which might respond differently from those grown in the field.

The objective here is to examine the effects of water table on specific physiological traits such as apparent photosynthetic rate, stomatal

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conductance and leaf water potential of soybean grown in a lysimeter.

### Materials and Methods

Experiments were conducted in lysimeters filled with alluvial soil in 1991 and 1992 at Tsukuba, and in 1992 at Fukuyama. In 1991, the treatments included three levels of water table (15, 40 and 70 cm below the soil surface) with no replication. Seeds of soybean cultivar "Tachinagaha" were sown in 60 cm rows with 15 cm intra-row spacing on June 17. Fertilizers were applied prior to sowing with rates ( $\text{g m}^{-2}$ ) of N : 3,  $\text{P}_2\text{O}_5$  : 10,  $\text{K}_2\text{O}$  : 10 and magnesium lime : 100, respectively. Seeds were inoculated with nodule bacteria (Konryu Bacteria) provided by Agricultural Research Institute, Tokachi Federation of Agricultural Cooperatives. Water table treatments were initiated five days after emergence. The plants were supported with vinyl cords to prevent lodging. In 1992, five treatments [4 levels of water table at 20, 40, 70 and 100 cm below the soil surface and control (no irrigation)] with no replication were applied at Tsukuba. Fertilizers were applied prior to sowing, with rates ( $\text{g m}^{-2}$ ) of N : 3,  $\text{K}_2\text{O}$  : 10 and magnesium lime : 100, respectively. Water table treatments were initiated at eight days after emergence. The other cultivation practices were the same as in the experiment in 1991. The experiment conducted at Fukuyama in 1992 used cultivar "Tamahomare" and consisted of the four treatments (3 levels of constant water table at 15, 40 and 60 cm below the soil surface, and one fluctuating water table between 15 and 40 cm) with two replicates. In the fluctuating water table treatment, water table was initially maintained at 40 cm for 1 month from July 24, and then raised to 15 cm until maturity. Fertilizers were applied prior to sowing, with rates ( $\text{g m}^{-2}$ ) of N : 1.5,  $\text{P}_2\text{O}_5$  : 5,  $\text{K}_2\text{O}$  : 5, respectively. Seeds were sown on July 30 in 65 cm rows with 15 cm intra-row spacing. Water table treatments were initiated 20 days after emergence.

Oxygen diffusive rate (ODR) of the soil was measured using a ODR meter (DIK-5100, Daiki Rika Kogyo Co. Ltd., Tokyo) on August 8 and August 22, 1991 when the soil was wet. The average ODR was computed based on readings from five platinum electrodes placed at 10 cm below the soil surface

in inter-row spaces. pF was measured using a tensiometer (DIK-3130, Daiki Rika Kogyo Co. Ltd.). Apparent photosynthesis and stomatal conductance of young, fully expanded leaflets were measured at saturated light intensity on clear days from the 4th week of July to the 1st week of September, by using a portable infrared gas analyzer (Analytical Development Co. Ltd.). Leaf water potential was measured by using a psychrometer chamber (Wescor Sample Chamber C-52-SF) and micro-volt meter (Wescor HR-33T) on July 29 and August 9, 1991 and August 18, 1992 at Tsukuba. Leaf xylem water potential was measured by pressure chamber (DIK-7000, Daiki Rika Kogyo Co. Ltd.) technique at Fukuyama on September 8, 1992. Chlorophyll content was determined using Minolta SPAD-502 on August 9, 1991 and August 18, 1992 at Tsukuba, and on September 8, 1992 at Fukuyama.

Yield of each plot were determined from harvest of 2.7  $\text{m}^2$  at Tsukuba in 1991, 1.2  $\text{m}^2$  at Tsukuba in 1992, 2  $\text{m}^2$  at Fukuyama in 1992.

### Results

#### 1. Oxygen diffusive rate (ODR)

ODR values at 10 cm below the soil surface were largely similar on both dates, August 8 and August 22 (Table 1). The values were very low ( $< 11 \times 10^{-8} \text{ g cm}^{-2} \text{ sec}^{-1}$ ) when water table was at 15 cm. ODR values increased with an increasing depth of water table but soil moisture tension (pF) values were similar in both 40 and 70 cm treatments.

#### 2. Apparent photosynthesis, stomatal conductance and water potential

##### (1) Results at Tsukuba

In 1991 (wet year), the effects of water table on pF values varied with changes in soil moisture status caused by rainfall as shown in Table 2. After eight successive clear days, pF values measured on July 29 (R1)<sup>8)</sup> at 10 cm depth were more than 2.9 when water tables were both at 40 cm and 70 cm. In such dry soil condition, apparent photosynthetic rate varied little (Fig. 1) but stomatal conductance and leaf water potential decreased with an increasing depth of water table (Figs. 2 and 3). The occurrence of rainfall (23 mm) on two consecutive days prior to August 9 (R3) led to a lowering of pF values (Table 2). In contrast to

Table 1. Effects of water table on soil oxygen diffusive rate and pF value measured at 10 cm below the soil surface in 1991 at Tsukuba.

| Date    | Depth of water table (cm) | Oxygen diffusive rate* ( $11 \times 10^{-8} \text{ g cm}^{-2} \text{ sec}^{-1}$ ) | pF  |
|---------|---------------------------|-----------------------------------------------------------------------------------|-----|
| Aug. 8  | 15                        | $6.6 \pm 0.83$                                                                    | 0   |
|         | 40                        | $34.1 \pm 2.96$                                                                   | 1.5 |
|         | 70                        | $51.1 \pm 3.59$                                                                   | 1.3 |
| Aug. 22 | 15                        | $10.8 \pm 0.95$                                                                   | 0   |
|         | 40                        | $40.8 \pm 2.59$                                                                   | 1.5 |
|         | 70                        | $45.8 \pm 5.54$                                                                   | 1.3 |

\*: Values represent the mean  $\pm$  SE of five samples.

Table 2. Effects of water table on pF value at different soil depth on photosynthesis measuring days in 1991 and 1992 at Tsukuba.

| Year | Date    | Depth of water table (cm) | Soil depth |      |      |      |
|------|---------|---------------------------|------------|------|------|------|
|      |         |                           | 10cm       | 20cm | 35cm | 50cm |
| 1991 | Jul. 29 | 15                        | 0          |      |      |      |
|      |         | 40                        | >3         | 2.0  | 0.8  |      |
|      |         | 70                        | >3         | >3   | 2.9  | 2.0  |
|      | Aug. 9  | 15                        | 0          |      |      |      |
|      |         | 40                        | 2.1        | 0.5  | 0.8  |      |
|      |         | 70                        | 1.9        | 2.6  | 2.6  | 2.4  |
| 1992 | Aug. 18 | 20                        | 1.4        |      |      |      |
|      |         | 40                        | 1.5        | 1.1  | 1.1  |      |
|      |         | 70                        | >3         | >3   | >3   | 1.8  |
|      |         | 100                       | >3         | >3   | >3   | >3   |
|      |         | No-irri.                  | >3         | >3   | >3   | >3   |
|      |         |                           |            |      |      |      |

the findings in dry soil, photosynthetic rate (Fig. 1) and leaf water potential (Fig. 3) increased with an increasing depth of water table in wet soil. Stomatal conductance was highest when water table was at 40 cm below the soil surface. Stomatal conductance in other treatments was largely similar (Fig. 2).

In 1992 (dry year), pF values at 10 cm, 20 cm and 35 cm depth were more than 3 in the deep water table treatments (>70 cm) on August 18. We did not have rainfall during August 14 to September 9. The apparent photosynthetic rate during pod-setting (R3) to seed-filling (R5) period was maximum when water table was at 40 cm below the soil surface (Fig. 4). The higher photosynthetic rate was accompanied by higher stomatal conductance in this treatment (Fig. 5). A gradual decline over time in apparent photosynthesis and stomatal conductance was observed in the control. The leaf water potential

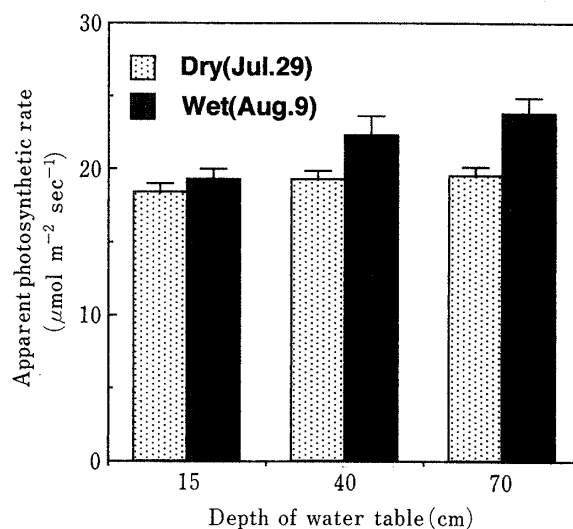


Fig. 1. Effects of water table on apparent photosynthetic rate of soybean at two contrasting soil moisture conditions (dry, wet) in 1991 at Tsukuba. The measurements were done between 11:00 and 14:00. Vertical bars denote standard errors of means (n=8).

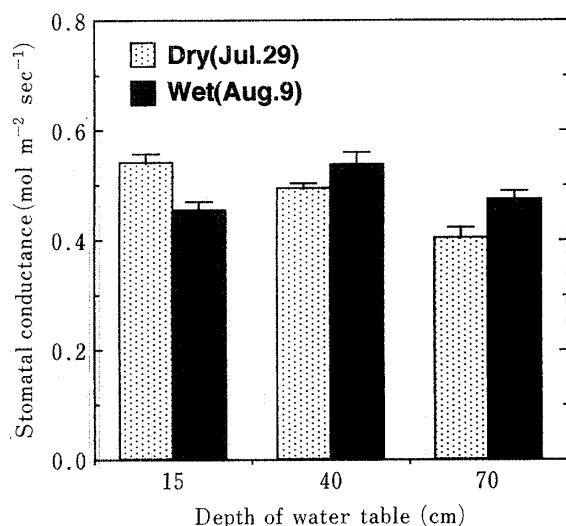


Fig. 2. Effects of water table on stomatal conductance of soybean at two contrasting soil moisture conditions (dry, wet) in 1991 at Tsukuba. The measurements were done between 11:00 and 14:00. Vertical bars denote standard errors of means ( $n=8$ ).

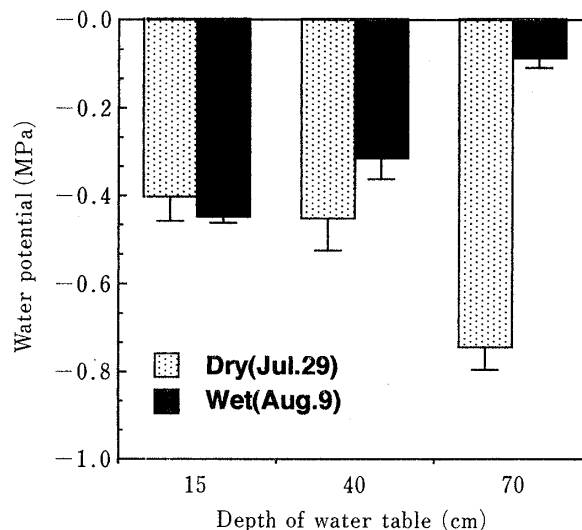


Fig. 3. Effects of water table on leaf water potential of soybean at two contrasting soil moisture conditions (dry, wet) in 1991 at Tsukuba. The measurements were done between 12:00 and 14:00. Vertical bars denote standard errors of means ( $n=5$ ).

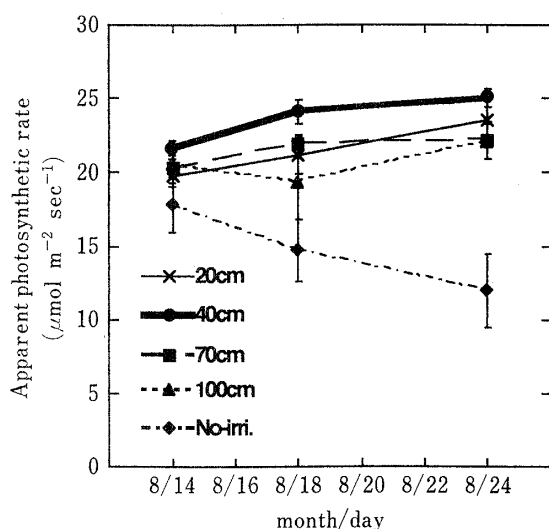


Fig. 4. Effects of water table on apparent photosynthetic rate of soybean during pod setting period in 1992 at Tsukuba. The measurements were done between 13:00 to 15:00. Vertical bars denote standard errors of means ( $n=6$ ).

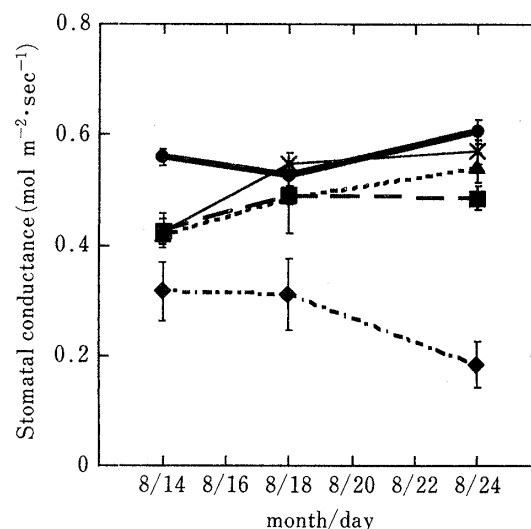


Fig. 5. Effects of water table on stomatal conductance of soybean during pod setting period in 1992 at Tsukuba. The measurements were done between 13:00 and 15:00. Vertical bars denote standard errors of means ( $n=6$ ). Symbols are as in Fig. 4.

measured in the morning of August 18 in the treatment with water table at 100 cm below the soil surface was slightly less ( $-0.4$  MPa) than in other treatments (ca.  $-0.2$  MPa) (Fig. 6). A decrease in water potential with an increase in depth of water table from 40 to 70 cm was observed during afternoon. The leaf

water potential during afternoon in the treatment with water table at 100 cm continued to be less ( $-0.5$  MPa) than in other treatments (ca.  $-0.35$  MPa) on August 24 (data not shown).

## (2) Results at Fukuyama

Apparent photosynthetic rates, measured

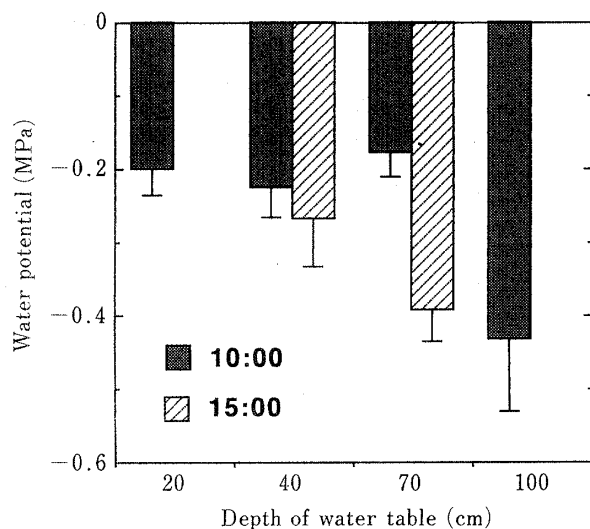


Fig. 6. Effects of water table on leaf water potential of soybean measured on Aug. 18, 1992 at Tsukuba. Vertical bars denote standard errors of means ( $n=6$ ).

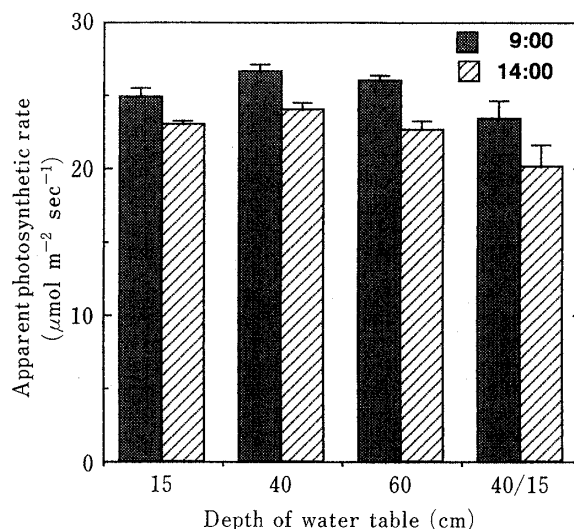


Fig. 7. Effects of water table on apparent photosynthetic rate of soybean measured on Sep. 8, 1992 at Fukuyama. Vertical bars denote standard errors of means ( $n=10$ ).

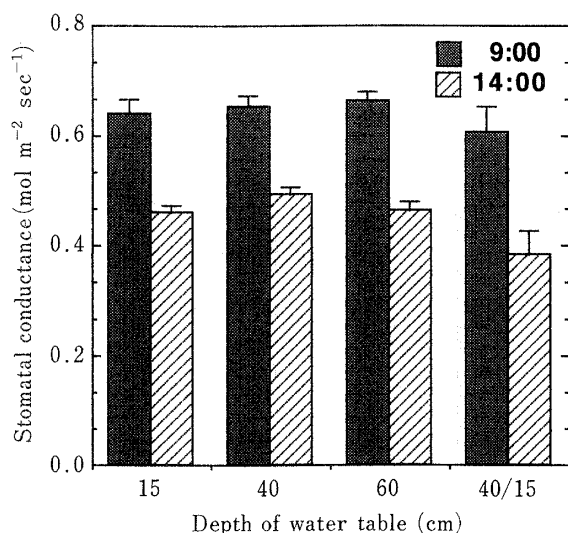


Fig. 8. Effects of water table on stomatal conductance of soybean measured on Sep. 8, 1992 at Fukuyama. Vertical bars denote standard errors of means ( $n=10$ ).

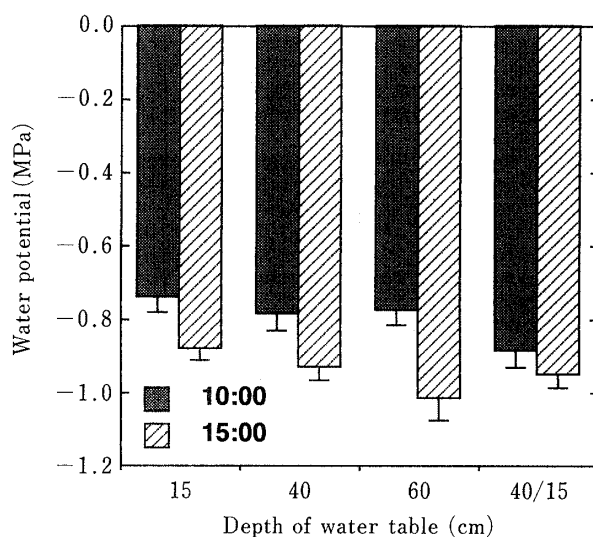


Fig. 9. Effects of water table on leaf xylem water potential of soybean measured on Sep. 8, 1992 at Fukuyama. Vertical bars denote standard errors of means ( $n=6$ ).

both in the morning and afternoon on September 8 (R5), were maximum when water table was at 40 cm below the soil surface and minimum in the fluctuating water table treatment (Fig. 7). A similar trend was seen in stomatal conductance (Fig. 8). Leaf water potential during morning did not vary with depth of water table but water potential in the fluctuating water table treatment was slightly less than in others. In the afternoon however, water potential decreased with an increasing

depth of water table from 15 to 60 cm (Fig. 9). The amount of rainfall was only 4 mm in two weeks till the measurement day. The upper soil layers looked very dry when water table was at 60 cm below the soil surface.

### 3. Relationships between chlorophyll content (SPAD value) and apparent photosynthetic rate

A significant positive correlation between leaf chlorophyll content and apparent photosynthetic rates was observed at Tsukuba

both in 1991 ( $r=0.56^{**}$ ,  $n=23$ ) and 1992 ( $r=0.50^{***}$ ,  $n=30$ ) (Table 3). However, no such correlation was observed at Fukuyama ( $r=0.22$ ,  $n=40$ ).

### Discussion

The results suggest that the effects of water table on photosynthesis and water relations of soybean vary with the changes in soil moisture status. Apparent photosynthetic rate did not vary much in a dry soil despite a decrease in leaf water potential and stomatal conductance, which in turn are perhaps due to poor water uptake, with an increase in depth of water table. In contrast, photosynthetic rate and water potential increased with an increasing depth of water table in wet soil. The increase in chlorophyll content (as indicated by SPAD values) with an increase in depth of water table, and a strong positive correlation between SPAD values and apparent photosynthesis in 1991 (Table 3) suggest that the higher rate of photosynthesis in treatments with deep water table was perhaps due to absence of excess water injury in those treatments, especially when soils were wet. The relatively high leaf water potential ( $> -0.5$  MPa) accompanied by small changes in stomatal conductance even in treatments with

deep water table was probably due to high water absorption associated with a better root growth in those treatments<sup>24</sup>). Thus the higher photosynthetic rates in treatments with deep water table may largely be due to an increased chlorophyll content.

The variation in results in 1991 and 1992 was probably due to differences in the amount of rainfall. Rainfall was less at Tsukuba in 1992<sup>24</sup>), and the highest water table treatment was 20 cm below the soil surface, which was 5 cm deeper than at Tsukuba in 1991 and at Fukuyama in 1992. Although the water table treatments with high SPAD value and apparent photosynthetic rate differed, a significant positive correlation between SPAD value and apparent photosynthetic rate was found at Tsukuba in both years (Table 3). Photosynthetic rate was maximum when water table was 40 cm both at Tsukuba and Fukuyama. However, SPAD values and photosynthetic rates were not closely correlated at Fukuyama. The reasons for such disparity of results in two locations are not clear from this study however.

#### 1. Factors affecting photosynthesis, stomatal conductance and leaf water potential

Photosynthesis in soybean is reported to be

Table 3. Effects of water table on SPAD, apparent photosynthetic rate, and correlation coefficient between SPAD and photosynthetic rate of soybean grown at Tsukuba and Fukuyama.

| Year | Location | Date    | Depth of water table (cm) | SPAD            | Apparent photosynthetic rate ( $\mu\text{mol m}^{-2} \text{sec}^{-1}$ ) | Correlation coefficient | n  | Yield ( $\text{g m}^{-2}$ ) |
|------|----------|---------|---------------------------|-----------------|-------------------------------------------------------------------------|-------------------------|----|-----------------------------|
| 1991 | Tsukuba  | Aug. 9  | 15                        | 45.3 $\pm$ 0.71 | 19.2 $\pm$ 0.78                                                         | 0.56**                  | 23 | 125.8                       |
|      |          |         | 40                        | 49.3 $\pm$ 0.52 | 22.2 $\pm$ 1.33                                                         |                         |    | 280.5                       |
|      |          |         | 70                        | 50.8 $\pm$ 0.68 | 23.7 $\pm$ 1.09                                                         |                         |    | 359.5                       |
| 1992 | Tsukuba  | Aug. 18 | 20                        | 47.5 $\pm$ 1.07 | 21.2 $\pm$ 1.24                                                         | 0.50**                  | 30 | 328.4                       |
|      |          |         | 40                        | 45.8 $\pm$ 0.44 | 24.0 $\pm$ 0.81                                                         |                         |    | 425.6                       |
|      |          |         | 70                        | 46.2 $\pm$ 0.75 | 21.9 $\pm$ 0.61                                                         |                         |    | 380.5                       |
|      |          |         | 100                       | 45.6 $\pm$ 1.11 | 19.3 $\pm$ 2.53                                                         |                         |    | 353.4                       |
|      |          |         | No-irri.                  | 44.7 $\pm$ 0.60 | 14.7 $\pm$ 2.08                                                         |                         |    | 183.1                       |
| 1992 | Fukuyama | Sep. 8  | 15                        | 43.1 $\pm$ 0.46 | 23.0 $\pm$ 0.30                                                         | 0.22 <sup>n.s.</sup>    | 40 | 264.9                       |
|      |          |         | 40                        | 45.7 $\pm$ 0.58 | 24.0 $\pm$ 0.49                                                         |                         |    | 343.1                       |
|      |          |         | 60                        | 46.2 $\pm$ 0.58 | 22.7 $\pm$ 0.54                                                         |                         |    | 344.1                       |
|      |          |         | 40/15                     | 44.2 $\pm$ 0.57 | 20.2 $\pm$ 1.43                                                         |                         |    | 292.0                       |

The apparent photosynthetic rates were measured between 14:00 and 15:00.

The SPAD and apparent photosynthetic rate were the average $\pm$ SE of eight (1991, Tsukuba), six (1992, Tsukuba) and ten (1992, Fukuyama) samples, respectively.

\*\* : Significant at 0.01 probability level. n.s. : Not significant.

positively correlated with chlorophyll content<sup>5,35</sup>, even when plants suffer from excess moisture injury<sup>29</sup>). However, there may be cases where other factors play a greater role. For instance, ODR increased with an increasing depth of water table despite no changes in pF (Table 1). The rapid downward movement of water in treatments with deep water table probably allowed availability of more oxygen to the roots. Sojka and Stolzy<sup>25</sup>) reported that stomatal resistance in many species increased exponentially when ODR was less than  $20 \times 10^{-8} \text{ g cm}^{-2} \text{ sec}^{-1}$ , even if there was enough moisture in the soil. The low values of ODR ( $< 11 \times 10^{-8} \text{ g cm}^{-2} \text{ sec}^{-1}$ ) in the treatment with water table at 15 cm below the soil surface (Table 1) may have led to a decreased stomatal conductance and apparent photosynthetic rate in wet soil condition.

Reicosky et al.<sup>22</sup>) reported that water uptake per unit length of roots just above the water table was much less than that of the other parts of the root system probably due to poor aeration. Other researchers<sup>18,34</sup>) noted that oxygen deficit caused by flooding increased root hydraulic resistance and resulted in shoot water deficit. On the other hand, there were reports when flooding did not cause shoot water deficit<sup>4,14,36</sup>). The critical values of leaf water potential for reducing apparent photosynthetic rate of soybean grown in pot<sup>3</sup>) or field<sup>33</sup>) were  $-1.1$  and  $-1.5$  MPa, respectively. Leaf water potentials observed in this experiment were always higher than these values. Therefore, factors other than low leaf water potential may account for reduced photosynthesis in treatments with water table at 15 or 20 cm. As excess moisture injury in soybeans can be alleviated by supplemental application of ammonium sulfate<sup>28</sup>) or foliar application of urea<sup>27</sup>), the reduced photosynthesis in treatments with shallow water table can, at least partly, due to low nitrogen absorption or fixation. The results suggest that the reduced photosynthesis in treatments with shallow water table was associated with low chlorophyll content, which in turn may be due to either low nitrogen availability or low stomatal conductance caused by a decreased oxygen supply to the root system rather than due to low availability of water.

Leaf water potential and stomatal conductance decreased with an increase in depth

of water table beyond 60 cm in dry soil condition in 1991 and 1992. In 1992 (dry year), apparent photosynthetic rate was also reduced. Reicosky et al.<sup>22</sup>) reported that the pattern of water absorption by soybean did not always reflect root distribution in different layers as most water was absorbed by one fifth of the total root length, which was mostly between 60 and 80 cm depth, in a treatment with water table at 100 cm. In our experiment at Tsukuba in 1992, two thirds of the total root length in the treatment with water table at 70 cm was in 0–20 cm layer<sup>24</sup>). The roots in this top layer are unlikely to contribute to water absorption, as pF was more than 3 in this layer. The low leaf water potential, stomatal conductance and apparent photosynthetic rate in treatments with water table at 70 and 100 cm below the soil surface thus seem to be due to the smaller amount of roots in the well watered region of the soil. The leaf water potential in these treatments (ca.  $-1.0$  MPa) was slightly higher than the critical value for reducing photosynthesis<sup>3,33</sup>).

We previously reported<sup>16</sup>) that midday depression of photosynthesis of field-grown soybeans could occur without a concurrent decrease in leaf water potential. The cultivar differences in midday depression of photosynthesis were partly due to differences in leaf water status, but a leaf water potential less than  $-1.0$  MPa was not observed in upland fields<sup>17</sup>). Bennett et al.<sup>2</sup>) also reported that stomatal conductance in moderately water stressed soybeans in the field was not closely related to changes in water potential, turgor potential, or relative water content. It is unclear however why photosynthesis was depressed even when the leaf water potential was not below  $-1.0$  MPa. There is a possibility that the roots in the upper dry soil layers sent some signals to shoot to reduce photosynthesis and stomatal conductance, as reported by Davies and Zhang<sup>7</sup>) and Bano et al.<sup>1</sup>) in other plants.

The apparent photosynthetic rate, stomatal conductance and water potential were less in the fluctuating water table treatment than in others. It is likely however that the plant root system did not adjust to the changes in water table yet, as the measurements were made only 15 days after raising the level of water table.

## 2. Photosynthesis and yield

In 1992, soybean yields were much less in treatments with water table at 15 (Tsukuba) or 20 cm (Fukuyama) than in the treatment with water table at 40 cm (Table 3). However, the differences in apparent photosynthetic rate among these treatments were relatively small. Apparent photosynthetic rates were measured only during summer when plants were likely to suffer from water deficits. In contrast, seed yields were determined over a long period and were probably influenced by many factors. It is therefore likely that the ranking in apparent photosynthetic rates in summer may not closely reflect variation in seed yields. Seed yield from the fluctuating water table treatment was higher than the treatment with water table 15 cm, although the apparent photosynthetic rate showed a reverse trend. The stem dry weight was more in the former, and the root system probably got adapted to the new condition<sup>26)</sup> after photosynthesis measurements were taken.

## Conclusion

Soybeans grown in saturated soil culture, where water table was kept at 10 cm below the soil surface, gave high yields in the semi-arid region of Australia during a dry season<sup>9,10,31,32)</sup>. Similarly, soybeans grown in greenhouse on water tables at 3 and 15 cm produced higher yields and fixed more nitrogen than those irrigated as per conventional method<sup>19)</sup>. These results imply that soybeans can give high yields even on shallow water table if there is no rainfall, and that the optimal water table for achieving high productivity seems to vary with rainfall.

Our results indicate that the depth and fluctuation of water table affect photosynthetic rate and water potential of soybean, and that the optimum water table depth for high photosynthesis vary with rainfall. The relatively low chlorophyll content and poor oxygen availability to the root in shallow water table treatments, and low water availability to the plant in deep water table treatments, seem to be responsible for reduced photosynthetic rate in such conditions. Because drained clayey paddy soils are inferior to upland fields of volcanic ash soil in both drainage and water supply<sup>11)</sup>, further efforts to maintain optimum water table are necessary for achieving high

rates of photosynthesis and high yields of soybeans<sup>24)</sup>.

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