Effects of Water Table Control by Farm-Oriented Enhancing Aquatic System on Photosynthesis, Nodule Nitrogen Fixation, and Yield of Soybeans

Shinji Shimada¹, Hideo Hamaguchi¹, Yeonghoo Kim¹, Kazuya Matsuura², Masayasu Kato¹, Takuo Kokuryu¹, Junko Tazawa¹ and Shinsaku Fujimori³

¹National Agricultural Research Center, NARO, 3-1-1 Kannondai, Tsukuba, Ibaraki 305-8666, Japan;
²Agricultural Research Institute, Ibaraki Agriculture Center, 3402 Kamikunii-cho, Mito, Ibaraki 311-4203, Japan;
³National Institute for Rural Engineering, NARO, 2-1-6 Kannondai, Tsukuba, Ibaraki 305-8609, Japan

Abstract: We evaluated the effects of the water table controlled by a water table controlling system, farm-oriented enhancing aquatic system (FOEAS), on soybean productivity. FOEAS was constructed in a heavy soil paddy field; we made plots with water tables maintained at −32 (water table depth [WTD]32) and −20 cm (WTD20) from the soil surface and, as a control, an open-ditch drained plot (ODD). Soybean cultivar “Tachinagaha” and non-nodulating cultivar “En1282” were cultivated in 2006 and 2007. The moisture of the topsoil in the water table-controlled plots showed less fluctuation owing to rainfall. The roots and nodules were distributed only in the upper soil layer in ODD, but more were distributed in deeper soil layers in WTD32 and WTD20. In Tachinagaha, the SPAD value and stomatal conductance were higher in WTD32 and WTD20 than in ODD, resulting in a higher apparent photosynthetic rate. The aboveground total dry weight and nitrogen accumulation of Tachinagaha were higher in the water table-controlled plots than in ODD; in En1282, this difference was insignificant. The relative ureide value which is an index of nodule activity, in ODD was depressed by both excess and deficit soil moisture; however, that in WTD32 remained relatively high during the growing stage. Tachinagaha showed higher yield in FOEAS plots, especially in WTD32 than in ODD in both years. The results indicate that control of water table by FOEAS increases nitrogen fixation, photosynthesis, and yield of soybeans in upland fields converted from paddy fields.

Key words: Nodule nitrogen fixation, Photosynthesis, Soybean, Water table, Yield.

Many upland crops are cultivated in temporarily drained paddy fields. More than 80% of soybean (Glycine max (L.) Merrill) acreage is located in upland fields converted from paddy fields (UCP) in Japan. The average soybean yield in Japan over the last 20 years was 1.64 t ha⁻¹, which is much lower than the average yield in the main soybean-producing countries, for example, 2.5 t ha⁻¹ in the U.S.A. and 2.3 t ha⁻¹ in Brazil (FAOSTAT, 1988−2007). Moreover, although the soybean productivity in Japan has not been improved in the last few decades, that in the U.S.A. and Brazil have been steadily increasing (Specht et al., 1999; Wilcox, 2001, 2004).

Soybean production in UCP tends to suffer from excess moisture injury because the UCP are often surrounded by paddy rice-cultivating fields where the water table is relatively high. A hard pan is often formed approximately 12 cm below the soil surface by soil puddling, which prevents water leakage during the cultivation of paddy rice; this leads to the formation of shallow root systems in soybeans (Mochida et al., 1990). The water table tends to be deeper during summer. In hot weather, drought often occurs and affects cultivated soybeans even in UCP. Some studies showed that soybean yields were very high (<5 t ha⁻¹) in UCP (Ohnuma et al., 1981; Nakaseko et al., 1984;
Shimada et al., 1990). However, most of UCP show very low and fluctuating yields. Therefore, an analysis of the factors that lead to high soybean yields in UCP is needed.

Previously, we pointed out that soybean growth and photosynthesis are affected by water table depth and stated that optimum water table depth for obtaining high yields exists, through a lysimeter experiment using gray lowland soil (Shimada et al., 1995, 1997). However, a precise control of the water table depth in the farmers’ fields was not possible. Recently, we developed a novel water table controlling system called the farm-oriented enhancing aquatic system (FOEAS) to regulate the water table depth from +20 to −30 cm from the soil surface in farmers’ fields (Fujimori, 2007). In FOEAS, irrigation water is supplied through a pipeline to the water supply control unit and flows into the trunk and branch pipes connected to the water level regulator located in the drainage side of the field. Mole drains are made at 1m intervals that meet at right angles to the trunk and branch pipes, for quick drainage and uniform distribution of irrigated water throughout the field. The system is expected to improve soybean productivity through control of the water table depth (Shimada, 2006).

Soybean production in paddy fields has been reported to accelerate the degradation of organic soil matter and reduces soil nitrogen fertility, regardless of continuous or rotational cropping (Sumida et al., 2005). The reduction of nitrogen fertility seems to be one of the reasons for a long-term reduction in soybean productivity. Consequently, it appears important to increase soil nitrogen fertility to improve soybean productivity. However, high soil nitrogen fertility promotes lodging and spoils the taste of rice (Ishima et al., 1974). Therefore, it is unrealistic to improve soybean productivity by increasing soil nitrogen fertility alone. Although nitrogen fertilization methods, including top dressing, have been developed, their effects are not always stable (Kuwahara, 1986a, 1986b; Salvagiotti et al., 2008). Nitrogen application is an expensive and laborious process. Therefore, a new cultivation technique for maximizing nodule nitrogen fixation needs to be developed (Shimada, 2006).

Nodule nitrogen fixation is known to be very sensitive to drought (Marino et al., 2007; Sinclair et al., 2007) and also stops at flooding (Huang et al., 1975). Furthermore, because leaf photosynthesis is affected by water table depth (Shimada et al., 1995), it is expected that nodule nitrogen fixation and leaf photosynthesis can be maintained at high levels by avoiding both drought and excess moisture injury caused by unfavorable rainfall and by controlling water table depth through the use of FOEAS. Therefore, we examined the effects of the use of FOEAS for control of water table depth on the physiological traits and productivity of soybeans such as nodule nitrogen fixation, photosynthesis, and seed yield in a low-nitrogen fertile paddy field with FOEAS installed.

Materials and methods

Three FOEASs were installed in a paddy field (2100 m²) located at the National Institute of Agro-Engineering (36°N, 140°E). The area of each FOEAS was approximately 500 m² with a 3-m-wide buffer area between systems to enable the water tables to be controlled individually. The soil of the field was clayey (LiC), with bulk density 1.1, pH 6.0, and total soil nitrogen 0.0016 g g⁻¹. Before soybean cultivation, paddy rice had been uniformly cultivated for more than 5 years. Soybean and wheat were planted from June 2006 to November 2007. Ground dolomite limestone, fused phosphate, and chemical fertilizer (0.03, 0.1, and 0.1 g g⁻¹ of N, P₂O₅, and K₂O, respectively) were applied at 120, 100, and 100 g m⁻², respectively, as basal fertilizers before sowing in both years. The seeds were inoculated with commercial rhizobia (Mamezo, Tokachi Nokyoren, Obihiro, Japan) before sowing in 2006. After the soybeans were harvested in 2006, 2000 g m⁻² barnyard manure was applied (0.003 g g⁻¹ total N).

Three seeds per hill were sown by hand, with 60 cm row width and 10 cm intra-row spacing, on 22 June 2006 and 20 June 2007. Plants were thinned to 1 plant per hill (16.7 plants m⁻²) at the first trifoliate stage. Two soybean cultivars, Tachinagaha (normal nodulating) and En1282 (non-nodulating; Francisco and Akao, 1993) were used for analyzing nodule nitrogen fixation, and three water table management systems were prepared. En1282 was a non-nodulating mutant line derived from cultivar Enrei whose maturity time is similar to that of Tachinagaha. The water table managements were as follows: (1) continuously controlled at −32 cm below the soil surface (water table depth [WTD]32) and (2) −20 cm (WTD20) plots and (3) an open-ditch drained (ODD) plot as a control. Water table control started on 30 June 2006 and 4 July 2007. The water level regulator of ODD plot was closed for invalidating underground drainage. ODD plots were not irrigated and were drained by open ditches to avoid raising the water table beyond −7 cm from the soil surface. The experiment was performed with a split-plot design with 1 year as a block, water table treatment as the main plot, and cultivar as the subplot with 3 replicates. The average volumetric soil water content between 0 and −20 cm soil depth was measured with a TDR sensor (EC-20, Decagon Devices Inc., Pullman, WA, USA). Water table depth was measured with a UIZ-WLR100 (Uizin Co., Tokyo, Japan). A terminal leaflet of the most active trifoliate leaf on the main stem was measured for leaf chlorophyll content (SPAD value) and photosynthetic rate. SPAD values were measured with SPAD-502 (Konica Minolta Holdings Inc., Tokyo, Japan), and apparent photosynthetic rate and stomatal conductance were measured between 1000 and 1400 with LI-6400 (LI-COR Biosciences, Lincoln, NE,
USA); carbon dioxide concentration was 380 ppm and photon flux density was 1800 µmol m$^{-2}$ s$^{-1}$. The roots and nodules were collected using an electric sampler with a core sampler (diameter, 9.5 cm; depth, 25 cm) (ES-30L; Fujiwara Scientific Co. Ltd., Tokyo, Japan) on October 10, 2006. Root length was measured using a Comair Root Length Scanner (Hawker De Havilland Victoria Ltd., Melbourne, Australia) and divided by sampled core volume to obtain the root length density (cm cm$^{-3}$). Leaf xylem water potential was measured between 1300 and 1400 hours on 25 August 2006, with a pressure chamber (Plant Moisture Tension Measuring Instrument Dik-7000; Daiki Rika Kogyo Co. Ltd., Tokyo, Japan). Xylem exudate was collected from 800 for one hour by absorbing on absorbent cotton. Concentrations of ureides (i.e., allantoin and allantoic acid), amino N, and nitrate in the xylem sap were measured using the method described by Young and Conway (1942), ninhydrin method (Takahashi et al., 1993), and Cataldo method (Cataldo et al., 1975), respectively. The relative abundance of ureide N (%) was calculated as described previously (Nohara et al., 2005). The estimated amount of nitrogen fixed in the nodules was calculated as described previously (Shiraiwa et al., 1994; Peoples et al., 2009). The dry weight was measured after drying at 85ºC for 72 hr. The seed crude protein, crude fat and total sugar were measured by near-infrared spectroscopy (Infratec 1241 Grain Analyzer, FOSS NIRSystems INC, Laurel, MD, USA). The conversion factor for the calculation of the crude protein content was 6.25. The reproductive growth stages (R1 to R8) are expressed according to Fehr et al. (1971). The sampling area of each replicate in

Fig. 1. Monthly climatic conditions in 2006 and 2007.

Fig. 2. Transitions of volumetric soil water content, water table depth, and precipitation in 2006. The vertical dotted lines indicate the date of relative ureide value measurement in Fig. 9.
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Tachinagaha and En1282 at maturity was 9.6 and 4.8 m², respectively. Statistical analysis was performed using Juse-StatWorks v4.0 (JUSE, Tokyo, Japan) and SPSS version 19 (SPSS, Inc., IBM Co, USA). Weather data were collected by the National Institute for Agro-Environmental Sciences, Japan which is located about 1.5 km from the experiment site.

Results

1. Meteorology, water table depth and soil moisture during the cultivation period

Compared with the weather in 2006, the weather in 2007 was hot with high solar radiation (Fig. 1). Precipitation in August was 74 mm in 2006, whereas it was only 24 mm in 2007. Precipitation in September was higher in 2007 than in 2006. However, approximately half of all precipitation in 2007 was due to torrential rain caused by Typhoon No. 9 (September 7, 2007). Thus, the weather in 2007 was drier during the grain-filling period than that in 2006.

Since the trends of water table depth and soil moisture due to precipitation were similar in 2006 and 2007, only the data obtained in 2006 are shown (Fig. 2). Water table depth fluctuated greatly between −10 and −55 cm from the soil surface in the ODD plots; on the other hand, water table depth in the plots controlled by FOEAS was highly stable at setting points owing to efficient drainage and sub-irrigation through the water supply control unit (Fujimori, Fig. 3. Effect of water table control on root length density (A) and dry weight of the nodule (B) of Tachinagaha at different soil layers, from the surface to 25 cm depth (2006). The horizontal bars represent the standard errors of 3 replicates. Samples were obtained on 10 October 2006.

Fig. 4. Effects of water table control on leaf chlorophyll content (SPAD value) of Tachinagaha and En1282. The vertical bars represent the standard errors of 15 replicates.

2006

2007
be higher in the WTD32 plots in 2006 and in the ODD plots in 2007. The stomatal conductance in Tachinagaha tended to be higher in WTD32 and WTD20 than in the ODD plots; conductance dropped largely in the ODD plots in late August in both years (Fig. 5). In the FOEAS plots (WTD32 and WTD20), stomatal conductance showed less fluctuation in the WTD32 and WTD20 plots owing to the control of the water table, as compared with ODD plots.

2. Root and nodule distribution

The average root length density between the soil surface and −25 cm depth was 0.94, 0.53, and 0.53 cm cm⁻³ in ODD, WTD32, and WTD20 plots, respectively (Fig. 3). The ODD plots showed the largest average root density; more than half of the roots were distributed in the uppermost (0−5 cm) layer. The WTD32 plots showed a relatively large root distribution below −15 cm depth. The average dry weight of the nodules between the soil surface and −25 cm depth was 0.7, 1.36, and 0.92 mg cm⁻³ in the ODD, WTD32, and WTD20 plots, respectively. The WTD32 plots had higher nodule dry weight than the other plots and the nodules were distributed in deep layers (−15 to −25 cm).

3. Leaf chlorophyll content, stomatal conductance, and apparent photosynthetic rate during the cultivation period

In Tachinagaha, the leaf chlorophyll content shown by the SPAD value was higher in WTD32 and WTD20 than in the ODD plots, especially during the later growth stage in both years (Fig. 4). The SPAD value of En1282 tended to be higher in the WTD32 plots in 2006 and in the ODD plots in 2007. The stomatal conductance in Tachinagaha tended to be higher in WTD32 and WTD20 than in the ODD plots; conductance dropped largely in the ODD plots in late August in both years (Fig. 5). In the FOEAS plots (WTD32 and WTD20), stomatal conductance in
August was higher in WTD32 plots in 2006, whereas it was higher in WTD20 plots in 2007. Leaf xylem water potential measured on the afternoon of 25 August 2006, was the highest in WTD32 followed by WTD20 and ODD plots (Fig. 6); this was the same order as the value of stomatal conductance measured on the same day (Fig. 5). The apparent photosynthetic rate tended to be higher in WTD32 and WTD20 than in the ODD plots (Fig. 5), which should be reflected by higher SPAD values and stomatal conductance in FOEAS plots.

4. **Aboveground total dry weight and nitrogen accumulation**

Aboveground total dry weight of Tachinagaha was the highest in the WTD32 plots after the R6 stage (full seed stage) in both years (Fig. 7). There was no obvious difference in aboveground total dry weight between the
WTD20 and ODD plots until the R6 stage. However, the aboveground total dry weight in the WTD20 plots was heavier after the R6 stage and the difference was significant at R8 (full maturity). On the other hand, the aboveground total dry weight of En1282 was much lighter than that of Tachinagaha; furthermore, there was no obvious difference between WTD32 and WTD20.

The change in the aboveground nitrogen accumulation during cultivation in both cultivars was similar to that in the aboveground total dry weight in 2006 (Fig. 8). In 2007, the aboveground total dry weight of Tachinagaha peaked at just after R6 whereas the aboveground nitrogen accumulation considerably increased after R6. At R8, the aboveground nitrogen accumulation in Tachinagaha was obviously greater in the WTD32 and WTD20 than in the ODD plots; however, the aboveground nitrogen accumulation in En1282 was approximately 10% that of Tachinagaha, and there were no differences between the plots in both years.

5. Nodule nitrogen fixating activity (2006)

There were no significant differences between the plots in the relative ureide value, which is an index of nodule nitrogen fixating activity on 11 August (Fig. 2A and Fig. 9 A) and 20 September (Fig. 2D and Fig. 9 D), when soil moisture fluctuated shortly before the measurements (Fig. 2). However, on 22 August just after soil moisture content was high (Fig. 2 B and Fig. 9B), and on 31 August when the soil was drying (Fig. 2C and Fig. 9C), significant differences were observed between the plots in the relative ureide value (Fig. 9). On 22 August when soil moisture was high (Fig. 2 B), the relative ureide value was highest in WTD32 followed by WTD20 and ODD in this order (Fig. 9). However, on 31 August when the soil was dry (Fig. 2 C) the relative ureide value was lower than in the ODD plots than in the other plots (Fig. 9).

The estimated amount of nitrogen fixed in the nodules was higher in the WTD32 and WTD20 plots than in the ODD plots (Fig. 10). The estimated proportion of nitrogen fixed in the nodules was higher in the WTD32 and WTD20 plots than in the ODD plots in 2007 and exceeded 85% in all plots.

6. Status of plants at maturity

The days from emergence to maturity in En1282 was not affected by the treatments, whereas those in Tachinagaha differed with the year (Table 1). In 2006, green stem syndrome tended to be slightly more common and maturity was delayed for 4 to 5 days in WTD20 plots compared with the other plots. In 2007, green stem syndrome was more severe and maturity was delayed by 11 to 14 days in the ODD plots compared with the WTD20 plots.

Tachinagaha had much larger stem growth than En1282. Main stem node number, total node number, and branch number were higher in 2007 than in 2006 in both cultivars. Branch number was the highest in the WTD32 plots in both years and cultivars.

7. Yield and yield components

The ripened pod number of Tachinagaha tended to be the highest in the WTD32 and the lowest in the ODD plots in both years (Table 2). Although the effect of the water
### Table 1. Effect of water table control on growth of 2 soybean cultivars examined at maturity.

| Year | Cultivar   | Treatment | Days from emergence to maturity | Degree of green stem syndrome | Degree of lodging | Main stem length (cm) | Main stem node number (plant⁻¹) | Total node number (plant⁻¹) | Branch number (plant⁻¹) |
|------|------------|-----------|---------------------------------|------------------------------|------------------|----------------------|--------------------------------|---------------------------|------------------------|
| 2006 | Tachinagaha| ODD       | 119                             | 1.0                          | 1.0              | 61.7                 | 13.7                          | 28.9                      | 3.2                    |
|      |            | WTD32     | 120                             | 1.0                          | 1.0              | 61.0                 | 13.5                          | 29.8                      | 3.5                    |
|      |            | WTD20     | 124                             | 2.0                          | 1.0              | 65.1                 | 13.8                          | 29.5                      | 3.3                    |
|      | En1282     | ODD       | 105                             | 0.0                          | 0.0              | 41.8                 | 13.0                          | 18.8                      | 1.6                    |
|      |            | WTD32     | 104                             | 0.0                          | 0.0              | 40.4                 | 13.0                          | 22.1                      | 2.2                    |
|      |            | WTD20     | 104                             | 0.0                          | 0.0              | 40.9                 | 13.0                          | 20.5                      | 2.0                    |
| 2007 | Tachinagaha| ODD       | 142                             | 4.0                          | 3.3              | 55.9                 | 14.2                          | 33.5                      | 4.2                    |
|      |            | WTD32     | 131                             | 2.0                          | 3.3              | 57.0                 | 14.3                          | 36.6                      | 4.6                    |
|      |            | WTD20     | 128                             | 1.3                          | 2.3              | 55.3                 | 14.2                          | 33.8                      | 4.3                    |
|      | En1282     | ODD       | 104                             | 0.0                          | 3.0              | 36.4                 | 13.7                          | 31.3                      | 3.8                    |
|      |            | WTD32     | 104                             | 0.0                          | 3.0              | 36.8                 | 13.7                          | 33.8                      | 4.4                    |
|      |            | WTD20     | 104                             | 0.0                          | 3.0              | 33.5                 | 13.5                          | 30.7                      | 4.0                    |

For ANOVA, the d.f. and p values are:

| Year | Cultivar | Treatment | d.f. | p values | A | Year | 1 | 0.137 | 0.405 | 0.004 | 0.067 | 0.019 | 0.005 | 0.001 |
|------|----------|-----------|------|----------|---|------|---|-------|-------|-------|-------|-------|-------|-------|-------|
|      |          |           | B   | Treatment | 2 | 0.659 | 0.746 | 0.5 | 0.94 | 0.984 | 0.136 | 0.095 | 0.023 |
|      |          |           | C   | Cultivar | 1 | <0.001 | <0.001 | 0.034 | <0.001 | <0.001 | 0.001 | 0.001 | 0.006 |
|      |          |           | BC  | T x C | 2 | 0.716 | 0.416 | 0.525 | 0.299 | 0.489 | 0.942 | 0.898 |

1) Emergence dates were 28 June 2006, and 26 June 2007.
2) Degrees of green stem syndrome and lodging are rated from 0 (none) to 5 (severe).
3) ANOVA of the split-plot design was performed with years as blocks, water table controls as the main plots, and cultivars as subplots.

### Table 2. Effect of water table control on yield and yield components in the 2 soybean cultivars.

| Year | Cultivar   | Treatment | Ripened pod number (pod m⁻²) | Seed number per pod (seed pod⁻¹) | 100-seeds weight (g) | Harvest index (g 100g⁻¹) | Seed yield¹ (kg 10a⁻¹) |
|------|------------|-----------|-------------------------------|---------------------------------|----------------------|-------------------------|------------------------|
| 2006 | Tachinagaha| ODD       | 423.2                         | 1.98                            | 39.6                 | 61                      | 331.7 b                |
|      |            | WTD32     | 530.5                         | 1.96                            | 38.3                 | 62                      | 398.2 a                |
|      |            | WTD20     | 477.6                         | 1.93                            | 41.0                 | 60                      | 379.1 a                |
|      | En1282     | ODD       | 87.3                          | 1.80                            | 16.0                 | 37                      | 25.2 b                 |
|      |            | WTD32     | 112.2                         | 1.88                            | 16.1                 | 39                      | 33.8 a                 |
|      |            | WTD20     | 105.0                         | 1.74                            | 17.6                 | 41                      | 32.0 ab                |
| 2007 | Tachinagaha| ODD       | 411.3                         | 1.80                            | 35.4                 | 51                      | 262.5 b                |
|      |            | WTD32     | 486.2                         | 1.88                            | 40.5                 | 58                      | 368.8 a                |
|      |            | WTD20     | 490.3                         | 1.87                            | 39.4                 | 59                      | 352.0 a                |
|      | En1282     | ODD       | 202.7                         | 1.76                            | 14.7                 | 39                      | 55.0                   |
|      |            | WTD32     | 164.3                         | 1.75                            | 14.3                 | 39                      | 41.1                   |
|      |            | WTD20     | 200.4                         | 1.65                            | 14.9                 | 42                      | 49.0                   |

For ANOVA, the d.f. and p values are:

| Year | Cultivar | Treatment | d.f. | p values | A | Year | 1 | 0.153 | 0.009 | 0.219 | 0.199 | 0.115 |
|------|----------|-----------|------|----------|---|------|---|-------|-------|-------|-------|-------|-------|
|      |          |           | B   | Treatment | 2 | 0.263 | 0.053 | 0.424 | 0.269 | 0.03  |
|      |          |           | C   | Cultivar | 1 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
|      |          |           | BC  | T x C | 2 | 0.153 | 0.227 | 0.333 | 0.551 | 0.03  |

1) 100-seeds weight and seed yield are expressed in 0.15 g g⁻¹ moisture.
2) ANOVA of the split-plot design was performed with years as blocks, water table controls as the main plots, and cultivars as subplots. Because there was an interaction between treatment and cultivar, a re-analysis was performed for each cultivar in each year. Means in columns followed by the same letters are not significant according to the Bonferroni method (p = 0.05).
table treatment varied with the year; there was no obvious trend in En1282. Although the effect of the water table control on seed number per pod and 100-seeds weight varied with the year in Tachinagaha, yearly fluctuation was larger in the ODD than that in the FOEAS plots. The seed yield of Tachinagaha increased significantly by water table control; in 2006 and 2007, the seed yield of the WTD32 plot was 20% and 40% more than that of the ODD plot, respectively. The seed yield of the WTD32 plots tended to be slightly higher than that of the WTD20 plots in both years. Non-nodulating En1282 showed lower ripened pod numbers, 100-seeds weights, and seed yields than did Tachinagaha. Furthermore, the effect of water table control on these yield components was unstable.

8. Seed components

The concentrations of crude protein, crude fat, and total sugar differed with the year (Table 3). Water table control tended to increase crude protein concentration compared to control. However, the optimal water table depth for achieving the highest crude protein content varied with the year. Crude fat was higher in 2006, whereas total sugar was higher in 2007. However, there was no definite effect of water table control on these parameters. Plants in the WTD20 plots showed very stable concentrations of these 3 components in both years.

Discussion

Water table control by FOEAS was effective in maintaining the water table depth even in heavy clayey soil which is poor in water permeability (Fig. 2). Since volumetric soil water content of topsoil fluctuated less in the FOEAS plots than in the ODD plots. FOEAS should improve the physiological functioning and productivity of soybean plants, as will be discussed later. The root distribution in the ODD plots was concentrated in the topmost layer of 5 cm depth (Fig. 3), because the water table depth was nearly −15 cm owing to a large amount of rain in July and August in 2006. The average root length density from the soil surface to −25 cm depth was the highest in the ODD plots; the roots in the upper layer seemed to absorb water for only a short period after rainfall. On the other hand, although the WTD32 and WTD20 plots with a stable water table had lower average root length density than the ODD plots, they could absorb a fairly large amount of water as indicated by stomatal conductance (Fig. 5) and leaf xylem water potential (Fig. 6). The average dry weight of the nodules was heavier in the FOEAS plots; the nodule dry weight in the WTD32 plots was twice that in the ODD plots (Fig. 3). FOEAS plots had relatively large amounts of nodules from −5 to −20 cm depth; that seems to contribute to increased nitrogen fixation. Relative ureide values can estimate point-in-time nodule nitrogen fixating activity (Peoples et al., 2009). Flooding did not occur in the ODD plots because water table depth did not exceed −7 cm. However, the relative ureide value was influenced by changes in soil moisture owing to rainfall (Fig. 9). Besides the observation on 22 August 2006 when the soil was very wet (Fig. 2B), the relative ureide value on 31 August, when the soil began to dry (Fig. 2C), was significantly lower in the ODD than in the WTD32 plots. It appears that the lower ureide value on 22 August was attributable to low oxygen availability to the nodules (Ae and Nishi, 1983).

The rate of exudation from the stem basal position in

Table 3. Effect of water table control on seed crude protein, crude fat, and total sugar in Tachinagaha.

| Year | Treatment | Crude protein (g 100 g$^{-1}$) | Crude fat (g 100 g$^{-1}$) | Total sugar (g 100 g$^{-1}$) |
|------|-----------|-------------------------------|---------------------------|-----------------------------|
| 2006 | ODD       | 42.1 b                        | 21.2 a                    | 21.3                        |
|      | WTD32     | 42.3 b                        | 20.6 b                    | 21.4                        |
|      | WTD20     | 43.7 a                        | 20.2 c                    | 21.5                        |
| 2007 | ODD       | 43.4                          | 19.5                      | 22.5 a                      |
|      | WTD32     | 44.0                          | 19.9                      | 21.7 b                      |
|      | WTD20     | 43.5                          | 20.3                      | 21.6 b                      |

ANOVA

|          | d.f. | p values |
|----------|------|----------|
| Year     | 1    | <0.001   |
| Treatment| 2    | 0.001    |
| Y × T    | 2    | 0.001    |

1) The data were measured by near-infrared spectroscopy and the concentrations were expressed on a dry weight basis.
2) The nitrogen-to-protein conversion factor is 6.25.
3) Because there was an interaction between year and treatment, a re-analysis was performed for each year. Means in columns followed by the same letter are not significant according to the Bonferroni method (p = 0.05).
the ODD, WTD20, and WTD32 plots on 31 August, 2006, was 48.62, and 69 mg min⁻¹ plant⁻¹, respectively. The rather high exudation rate in the ODD plot indicates that water deficit stress was not very severe; however, the relative ureide value was obviously lower in ODD than in WTD32 and WTD20 plots. In soybean plants, the effect of drought on nodule nitrogen fixation is more severe than that on photosynthesis (Sinclair et al., 1987; Sall and Sinclair, 1991); even a mild drought inhibits nodule nitrogen fixation (Sinclair and Serraj, 1995). Soybean plants in FOEAs plots maintained high nodule activity because they could easily absorb sufficient water because of the stable water table, whereas plants in the ODD plots could not absorb sufficient water because the soil where roots existed was dry. The data indicate that without water table control, nodule nitrogen fixation was considerably affected by rainfall. Therefore, nodule nitrogen fixation during the seed-filling period can be substantially improved if the water table is held at approximately ~30 cm.

The estimated amount of nitrogen-fixed by nodules was calculated using the difference method: total aboveground nitrogen accumulation of nodulating soybeans minus that of non-nodulating soybeans. Shiraiwa et al. (1994) evaluated the nitrogen-fixing activity of 15 new and old cultivars by subtracting the nitrogen accumulation of a non-nodulating cultivar. The results of the difference method are corroborated by those of the isotope dilution technique under conditions of very low soil nitrogen availability (Vasilas and Ham, 1984); therefore, this method could accurately evaluate nodule nitrogen fixation activity (Peoples et al., 2009). Thus, the evaluation of nodule nitrogen fixation in our experiment is reliable, because the soybean plants were cultivated in a very low nitrogen fertile soil and the yield of the non-nodulating cultivar was quite low (<53 g m⁻²). The results indicate that water table control obviously improves the nodule nitrogen fixation of soybean plants. In WTD32 plots, Tachinagaha fixed 22.2 g m⁻² N; the average proportion of fixed nitrogen over both years reached 93 g 100g⁻¹ N. Soybean plant is one of legumes with the highest nodule nitrogen fixing activity and appears to be able to fix more than 30 g m⁻² N in a crop year (Unkovich and Pate, 2000; Shimada, 2006; Campo et al., 2009).

There is a close relationship between aboveground nitrogen accumulation and seed yield (Salvagiotti et al., 2008). The seed production efficiency of nitrogen, i.e., kilogram seed weight (converted to 0.15 g g⁻¹ seed moisture content) per kilogram nitrogen accumulated in aboveground biomass, from 637 datasets ranged from 6.6 to 19.2 kg with a mean of 13.0 kg (Salvagiotti et al., 2008); The efficiency in the present experiment ranged from 14.4 to 16.7 kg and is similar to 14.5 to 15.9 kg reported by Ohnuma et al. (1981). Salvagiotti et al. (2008) stated that soybean yield is more likely to respond to nitrogen fertilization in high-yield (>450 g m⁻²) environments. Hence, soybean plants are able to fix enough nitrogen to achieve up to 450 g m⁻² seed yield under favorable conditions for nodule nitrogen fixation. Although the amount fixed in the nodules did not reach 30 g m⁻² nitrogen in the present study, Tachinagaha appears to fix sufficient nitrogen to achieve approximately 400 g m⁻² seed yield in the Kanto District with water table control and good weather conditions.

The SPAD value, which indicates leaf chlorophyll content, was much higher in the FOEAs plots than in the ODD plots. The stomatal conductance in the ODD plots was lower than that of the other plots in late August owing to drought. The photosynthetic rate of soybean plants encountering the rainy season during the early growth stage is low after summer, resulting in low seed yield, as compared with plants that do not encounter rainfall during the rainy season (Hirasawa et al., 1998). Because FOEAs plots had a rather high drainage capacity because the mole drains were installed at approximately ~40 cm depth with 1-m intervals (Fujimori, 2007), root systems were more luxuriant between ~15 and ~20 cm depth in the WTD32 and WTD20 plots compared with the ODD plots. This larger root system in the soil layer should contribute to the higher stomatal conductance and photosynthetic rate observed in the FOEAs plots. The stomatal conductance was higher in the WTD20 than in the WTD32 plots on 26 August 2007; The maximum temperature on this day was 34.3°C, and the soil was considerably dry because only 7 mm of precipitation was recorded in the week before the measurement. Therefore, the plants in WTD32 plots seem to have experienced slight water deficit stress even though the water table was maintained. The higher yield in the FOEAs plots compared with the ODD plots seems to be attributable to higher photosynthetic activity during the seed-filling period, which is the most important stage for achieving high yields in soybeans (Shiraiwa et al., 2004). Both the aboveground dry weight (Fig. 7) and aboveground nitrogen level (Fig. 8) of the non-nodulating cultivar En1282 were much lower than those of the nodulating cultivar Tachinagaha; this was due to low nitrogen availability from the soil and fertilizer. In En1282, the aboveground dry weight and nitrogen accumulation after R6 were slightly higher in 2007 than in 2006 because 2 t ha⁻¹ barnyard manure was applied after harvesting in 2006. The aboveground dry weights of Tachinagaha on 20 September were similar (approximately 600 g m⁻²) in both 2006 and 2007, whereas the aboveground nitrogen accumulation was much smaller in 2007 than in 2006. This discrepancy is probably attributable to the higher dry weight partitioning to the pods and seeds, which contain a relatively large amount of nitrogen (approximately 0.045 g g⁻¹), in 2006; the dry weight of pods was 290 and 90 g m⁻² in 2006 and 2007, respectively.

The maturity date, degree of green stem syndrome, and
lodging in Tachinagaha varied with the year. In the WTD20 plots, Tachinagaha tended to mature later and had a higher degree of green stem syndrome in 2006 (Table 1). The wet soil conditions due to abundant rainfall in October 2006 seem to have increased the degree of green stem syndrome. Sato et al. (2007) reported that green stem syndrome (i.e., delayed stem senescence) is considerably severe under wet soil conditions. However, the degree of green stem syndrome was very severe and maturity was considerably delayed in the ODD plots in which plants seemed to be water stressed during midsummer, as shown by low stomatal conductance and photosynthetic rate in 2007 (Fig. 5).

The effects of water table control on seed number per pod and 100-seeds weight were not obvious, but ripened pod number tended to increase and seed yield increased significantly in the FOEAS plots. Seed yield was the highest in the WTD32 plots in both years. There were no obvious effects of water table control on En1282 growth at maturity (Table 1), yield, and yield components (Table 2). It is known that the seed yield of non-nodulating soybeans increases linearly with the application of nitrogen fertilizer (Weber, 1966). The direct application of barnyard manure increased the growth and yield of En1282 in 2007, whereas its effect on the yield of Tachinagaha was not obvious. The amounts of aboveground nitrogen of En1282 at maturity ranged from 1.2 to 2.6 g m\(^{-2}\), indicating that the soil nitrogen fertility was very low for soybean growth. Thus, the proportion of fixed to total nitrogen was quite high, and the yield was strongly influenced by water table control, because nodule nitrogen fixation in Tachinagaha is quite sensitive to soil moisture content (Fig. 10).

Our results indicate that the effects of water table control on seed components tend to be more obvious with respect to protein than fat. Furthermore, the results regarding the effects of soil moisture on seed components were similar to those reported by Ueda (1952). Both excess and deficits in soil moisture may reduce the protein concentration in soybean seeds (Koshiha, 1955). Therefore, it is expected that controlling the water table will result in relatively high and stable protein concentrations in soybeans. However, more data needs to be collected before a conclusion can be reached.

We will examine the effects of FOEAS on many aspects of soybean production in paddy fields, such as improving the efficiency of farm operations and adaptability to non-tillage cultivation.

**Conclusion**

The present results indicate that water table control by FOEAS alleviates fluctuations in soil moisture in topsoil and increases nodule nitrogen fixation and the photosynthetic rate in soybean plants. These effects contribute to a high seed yield even in the field with low nitrogen fertility. The optimal water table depth is approximately ~30 cm, which is the lowest available setting position of FOEAS.

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