Changes in Seed Quality during Maturation of Sunflower under High or Changeable Water Table Conditions

Satoko Yasumoto and Morio Matsuzaki

(Biomass Production and Processing Team, Institute of the National Agricultural Research Center, 3-1-1 Kannondai, Tsukuba 305-8666, Japan)

Abstract: Growth, yield and quality of sunflower (*Helianthus annuus* L.) in a rotational paddy field were compared with those in an upland field. In the rotational paddy field the growth was significantly suppressed and the seed and oil yields were significantly lower than those in the upland field. In the maturing period, oil accumulated in seeds until about 25 days after flowering (DAF) in both fields, but less in the rotational paddy field than in the upland field. Differences in oil contents (per seed) between the fields were seen from about 25 DAF onward. The fatty acid in seeds changed with maturing of plants. In mid-oleic hybrids, oleic acid increased remarkably until about 25 DAF and then decreased slightly; linoleic acid content decreased until about 14 DAF and then tended to increase. In linoleic acid hybrids, oleic acid increased until about 14 DAF and then decreased; the linoleic acid content tended to be low until about 14 DAF and then increased. Although the temporal patterns of fatty acid compositions during seed maturation were similar in both fields, the oleic acid content tended to be lower in the rotational paddy field even under the same climatic conditions and ripening periods. The differences between the fields were seen clearly from around 25 DAF. We discuss our findings with regard to physiological changes in developing seeds and the effects of high or changeable soil moisture content on sunflower growth and quality.

Key words: Maturation, Rotational paddy field, Seed quality, Sunflower.

Monounsaturated fatty acids, such as oleic acid and palmitoleic acid, have antioxidant properties and they may improve many of the metabolic processes in humans and may increase antioxidant (Berry, 1997). Oleic acid has been shown to help prevent coronary artery disease (Ma et al., 1997). Krajičvičová-Kudlácová et al. (1997) reported that a diet rich in monounsaturated fatty acids prevents cardiovascular diseases. It is important to understand the physiological properties of sunflower (*Helianthus annuus* L.), a plant with a high oleic acid content and the change of quality with maturation.

Several studies have analyzed the oil content and the fatty acid compositions in developing seeds of sunflower. The changes of seed oil percentage, fatty acid compositions and dry weight with seed maturation (Robertson et al., 1978) and the changes in fatty acid compositions and the effects of temperature condition (Martínez-Force et al., 1998) have been analyzed. Baydar and Erbaş (2005) tracked changes in the quality of linoleic hybrid seeds and found that the oil content increased, oleic acid content decreased, and linoleic acid content increased during the seed maturation process. Sobrino et al. (2003) reported that the temperature during development and maturation of sunflower achenes was the most important factor for the production of oleic acid.

We have been conducting studies on the cultivation of sunflower in rotational paddy fields and upland fields that were abandoned due to poor drainage, for the purpose of producing oil for human consumption and for use as biodiesel fuel. For successful cultivation of *H. annuus* in such fields in monsoon Asia, it is important to understand the responses of sunflower to high water table and waterlogging conditions. Several previous studies examined the effects of short-term waterlogging on sunflower. Orchard and Jessop (1984) reported that waterlogging at anthesis reduced seed yield more than it did at the six-leaf and visible-bud stages. Waterlogging during the vegetative and floral initiation stages inhibited leaf expansion (Orchard et al., 1986). Grassini et al. (2007) reported that waterlogging during the grain-filling stage caused adverse physiological responses: leaf area, leaf capacity to fix carbon, water absorption, and grain yield all decreased. Yasumoto et al. (2011) reported the effects of a high water table and short-term flooding on growth, yield, and seed quality of sunflower. We found that a high water table suppressed...
root growth, thus decreased plant growth and shortened the ripening period, and decreased seed weight and oil content.

Although studies on the changes in the components of sunflower seeds during maturation have been reported, the plants were grown in upland fields or controlled growth chambers (Martínez-Force et al., 1998; Baydar and Erbaş, 2005); and, the changes of quality in maturing period under conditions of high or changeable soil moisture content, such as that in rotational paddy fields or fields with poor drainage have not been reported. In the present study, we analyzed the changes in seed quality of mid-oleic and linoleic acid sunflower hybrids grown in rotational paddy fields. The objective was to clarify the physiological changes that occur in sunflower seeds during maturation, and ultimately to apply the information for improving the yield and quality of sunflower seeds grown in fields with high or changeable soil moisture conditions, such as rotational irrigated paddy fields and fields with poor drainage.

Materials and Methods

1. Effects of soil moisture conditions on the development, growth, yield, and quality of seeds

The first experiment was conducted in 2010 and 2011 in a rotational paddy field after a crop of irrigated rice and in an upland field at Tsukubamirai city in Ibaraki prefecture. Eight H. annuus cultivars were used: three were mid-oleic hybrids, ’63M80’, ’Hysun511’ and ’IS4704NS’; three were linoleic hybrids, ’Hybrid-sunflower’, ’North Queen’ and ’Short Stem’; and two were genetic resources, ’Armarvirskij3497’ (Arm.) (Accession No. 33526), and ’Line41’ (Accession No. 209128). Seeds were sown on 25 June 2010 and 17 May 2011 at a spacing of 25 cm between plants and 60 cm between rows. A compound fertilizer was broadcast prior to planting to provide 8.4, 7.0, and 7.0 g m$^{-2}$, respectively, of nitrogen (N; as [NH$_4$]$_2$SO$_4$), phosphorus (as P$_2$O$_5$), and potassium (as K$_2$O), in both fields. Top dressing was applied at 10.0 g m$^{-2}$ of N (as [NH$_4$]$_2$SO$_4$) in both fields about a month after sowing (on 27 July 2010 and 30 June 2011).

Flowering time, seed maturation time, plant height, stem length, head diameter, leaf number, and N content of the leaf were measured using the methods described by Yasumoto et al. (2011). We collected average and minimum temperature data using a weather station (Weather Data Acquisition System of the National Agricultural Research Center) located in the experimental fields in Tsukubamirai city in Ibaraki Prefecture. Before flowering and at flowering in 2011, the leaf N content was measured using a handheld optical sensor (SPAD-502, Konica Minolta, Inc., Tokyo, Japan), as described by Yasumoto et al. (2011). The volumetric soil moisture content was measured using a soil moisture probe (Profile Probe PR2, Daiki Rika Kogyo Co. Ltd., Tokyo, Japan), with pipes installed at three randomly selected plots in each field. The soil moisture was measured at depths of 10, 20, 30, 40, 60, and 100 cm about twice a week, and averages of the measured values from the three plots were used to represent the overall soil moisture for each field. Yield of each plot was determined based on the harvest of 1.2 m$^2$.

Oil concentration and oil content of seed and 1000-kernel weight were measured at the physiological mature stage (R-9; Schneider and Miller, 1981). Oil concentration represented the percentage and the oil content showed the amount in one seed. To determine the oil concentration, oil content and fatty acid content of seeds, 2 g of seeds from each sample were crushed using an automated mill and the oil was extracted with n-butyl alcohol. They were determined by the Caviezels method (Pendl et al., 1998), using a gas chromatograph (B-820, Nihon Büch Co. Ltd., Tokyo, Japan). The content of each fatty acid was calculated as the percentage of the area under the corresponding peak to the total peak area (Yasumoto et al., 2011). All treatments were performed two or three times depending on the cultivars.

2. Changes in seed quality, 1000-kernel weight, oil concentration, oil content, and fatty acid composition during seed development

The second experiment was conducted in 2010 and 2011 in an upland field and a rotational paddy field after a crop of irrigated rice at Tsukubamirai city in Ibaraki Prefecture. Fertilizer application was the same as in the first experiment. Four H. annuus cultivars were used: in 2010, we used ’Hysun511’, ’63M80’, ’North Queen’ and ’Hybrid-sunflower’. In 2011, we used ’IS4704NS’, ’63M80’, ’North Queen’ and ’Hybrid-sunflower’. The first two were mid-oleic hybrids and the second two were linoleic hybrids. Seeds were sown on 25 June 2010 and 17 May 2011 at a spacing of 25 cm between plants and 60 cm between rows. The start of flowering was recorded in all hybrids. Average and minimum temperature data were collected from a weather station in the study field, as in the first experiment.

Plants that started flowering at about the same time in both fields were labeled with the same color of tape, and then the heads were covered with mesh bags for protection against birds. The heads of three to five plants were collected at 10, 14, 25, 30, 40, and 50 DAF. The harvested flowers were immediately frozen in liquid nitrogen and then stored at −20°C. Seeds were collected from 3 – 5 cm of the flower head edge and vacuum-freeze dried (FD-2BM-400, Nihon Techno Service Co., Ibaraki, Japan). The oil content and fatty acid composition of the seeds were determined as in the first experiment. All treatments were performed three to five times depending on the hybrids.
Table 1. Growth parameters of sunflower in the rotational paddy field in 2010.

| Field                | Cultivar                  | Flowering time | Maturing time | Days to flowering time | Days to maturing time | Ripening period (days) | Avg. Temp. (ºC) | Cumulative Temp. (ºC) | Plant height (cm) | Stem length (cm) | Leaf number | Head diameter (cm) |
|----------------------|---------------------------|----------------|---------------|------------------------|------------------------|------------------------|-----------------|---------------------|------------------|-----------------|-------------|-------------------|
|                      |                           |                |               |                        |                        |                        |                 |                     |                  |                 |             |                   |
| Rotational paddy field | Mid-Oleic F1 hybrid      | 63M80          | 63M80         | 14 August              | 54 ab                  | 88 b                   | 35 ab            | 102 bc              | 102 ab           | 102 ab          | 33.0 a      | 8.6 ab            |
|                      |                           | IS4704NS       | IS4704NS      | 11 August              | 51 d                   | 78 c                   | 31 c             | 103 ab              | 103 ab           | 103 ab          | 30.3 a      | 9.3 ab            |
|                      | Linoleic F1 hybrid        | Hybrid-sunflower| Hybrid-sunflower | 16 August              | 57 a                   | 85 a                   | 33 bc            | 105 bc              | 105 ab           | 105 ab          | 31.6 a      | 9.7 ab            |
|                      |                           | North Queen    | North Queen   | 8 August               | 52 c d                 | 80 bc                  | 36 ab            | 985 ab              | 127 ab           | 127 ab          | 35.7 a      | 7.8 b             |
|                      |                           | Short stem     | Short stem    | 3 August               | 48 e                   | 78 c                   | 39 a             | 1087 a              | 80 c             | 74 c            | 23.7 b      | 8.6 ab            |
| Genetic resources    | Arm.¹)                   | 13 August      | 13 August     | 16 September           | 53 bc                  | 84 a                   | 35 ab            | 27.3 bc              | 955 bc           | 150 a           | 144 a       | 33.2 a            |
|                      |                           | Line41         | Line41        | 12 August              | 52 c d                 | 84 a                   | 36 ab            | 27.3 bc              | 968 b           | 146 a           | 140 a       | 33.3 a            |
| Upland field         | Mid-Oleic F1 hybrid      | 63M80          | 63M80         | 13 August              | 53 a                   | 100 ab                 | 51               | 25.1 a               | 1272             | 154 b           | 147 bc      | 33.3 ab           |
|                      |                           | IS4704NS       | IS4704NS      | 11 August              | 51 a                   | 90 b                   | 43               | 26.9 b               | 1142             | 135 c           | 127 c       | 28.2 bc           |
|                      | Linoleic F1 hybrid        | Hybrid-sunflower| Hybrid-sunflower | 15 August              | 55 a                   | 100 ab                 | 49               | 25.0 a               | 1218             | 173 a           | 166 ab      | 31.9 abc          |
|                      |                           | North Queen    | North Queen   | 9 August               | 51 a                   | 98 ab                  | 48               | 26.4 b               | 1262             | 181 a           | 175 a       | 35.8 a            |
|                      |                           | Short stem     | Short stem    | 4 August               | 43 b                   | 90 b                   | 50               | 27.0 b               | 1351             | 101 c           | 94 d        | 27.1 c            |
| Genetic resources    | Arm.¹)                   | 14 August      | 14 August     | 5 October              | 54 a                   | 101 a                  | 51               | 25.0 a               | 1261             | 185 a           | 178 a       | 37.1 a            |
|                      |                           | Line41         | Line41        | 12 August              | 51 a                   | 98 b                   | 50               | 25.3 a               | 1267             | 162 b           | 155 abc     | 34.6 ab           |

** and ***: significant at the 5% and 1% levels, respectively. Values followed by the same letter in a column are not significantly different at the 5% level by Tukey’s test.

¹Arm.: Armarvirski8497.
Table 2. Growth parameters of sunflower in the rotational paddy field in 2011.

| Field                  | Cultivar                  | Flowering time | Maturing time | Days to flowering time | Days to maturing time | Ripening period (days) | Avg. Temp. (ºC) | Cumulative Temp. (ºC) | Plant height (cm) | Stem length (cm) | Leaf number | Head diameter (cm) | N (%) |
|------------------------|----------------------------|----------------|---------------|-------------------------|------------------------|------------------------|-----------------|----------------------|-------------------|------------------|-------------|------------------|-------|
| Rotational paddy field | Mid-Oleic F1 hybrid       | 22 July 4 September | 67 abc 111 45 ab 25.6 bc 1166 ab | 86 e | 82 e | 20.2 bc 10.6 c | 4.9 | 2.4 d |
|                        | IS4704NS                   | 22 July 4 September | 67 abc 111 45 ab 25.6 c 1164 ab | 99 d | 94 d | 21.4 b 11.8 bc | 4.1 | 3.2 bc |
| Linoleic F1 hybrid     | Hybrid-sunflower           | 29 July 5 September | 75 a 112 39 b 26.0 a 1026 ab | 122 b | 116 b | 20.5 bc 12.3 a | 4.4 | 3.5 b |
|                        | North Queen                | 19 July 3 September | 64 c 110 47 a 25.5 c 1224 a | 138 a | 133 a | 24.2 a 11.9 abc | 4.6 | 4.7 a |
|                        | Short stem                 | 21 July 5 September | 66 bc 112 47 a 25.5 c 1226 a | 108 cd | 103 cd | 18.1 d 12.1 ab | 4.4 | 2.6 cd |
| Genetic resources      | Arm. 1)                    | 29 July 3 September | 74 ab 110 38 b 26.0 a 1000 b | 117 bc | 112 bc | 20.5 bc 12.5 a | 4.3 | 2.8 cd |
|                        | Line41                     | 24 July 5 September | 69 abc 112 44 ab 25.9 ab 1165 ab | 117 bc | 111 bc | 19.6 cd 13.1 a | 3.8 | 3.1 bcd |
| Upland field           | Mid-Oleic F1 hybrid       | 20 July 6 September | 65 113 49 25.5 1264 | 140 c | 133 c | 23.4 b 13.6 bc | 3.1 e | 4.3 bcd |
|                        | IS4704NS                   | 20 July 7 September | 65 114 50 25.5 1287 | 138 c | 130 c | 23.9 b 16.5 a | 4.3 ab | 4.0 bc |
| Linoleic F1 hybrid     | Hybrid-sunflower           | 23 July 8 September | 69 115 48 25.7 1232 | 166 b | 160 ab | 24.4 ab 15.5 ab | 4.6 a | 4.9 a |
|                        | North Queen                | 16 July 3 September | 62 110 50 25.6 1296 | 165 b | 158 b | 26.5 a 14.8 abc | 4.0 bc | 4.8 ab |
|                        | Short stem                 | 17 July 5 September | 62 112 51 25.7 1335 | 117 d | 111 d | 11.8 c 12.3 c | 3.7 bcd | 3.6 cd |
| Genetic resources      | Arm. 1)                    | 21 July 5 September | 67 112 47 25.5 1212 | 179 a | 172 a | 24.6 ab 17.2 a | 3.4 ce | 4.4 ab |
|                        | Line41                     | 19 July 8 September | 65 115 51 25.5 1324 | 156 b | 150 b | 23.3 b 16.5 ab | 3.4 de | 3.2 d |

1) Arm.: Armavirskij3497.

* and **: significant at the 5% and 1% levels, respectively. Values followed by the same letter in a column are not significantly different at the 5% level by Tukey's test.
3. **Statistical analysis**

All statistical analyses were performed with SPSS (ver. 11.0J for Windows; SPSS Japan Inc., Tokyo, Japan). All values are expressed as mean values. The data were analyzed by using analysis of variance, and statistically significant differences between treatments were determined by Tukey’s test at $P < 0.05$.

**Results**

1. **Field conditions during cultivation**

   In 2010, the earliest flowering date was 3 August and the latest seed maturation date was 3 October (Table 1). During this period, soil moisture content was always higher in the rotational paddy field than in the upland field at most depths (Fig. 1). In 2011, the earliest flowering date was 16 July and the latest seed maturation date was 8 September (Table 2). During this period, soil moisture content at depths of 10 and 20 cm was always higher in the rotational paddy field than in the upland field. At depths of 30 – 60 cm, the soil moisture content in the rotational paddy field showed much greater variability than that in the upland field (Fig. 1).

![Soil moisture conditions during cultivation in the two fields in 2010 and 2011.](image)

- ■, rotational paddy field; ◇, upland field. Error bars represent the standard error of the mean ($n = 3$).
Yasumoto and Matsuzaki — Changes during Maturation of Sunflower under High or Changeable Water Table Conditions

The temporal patterns of average and minimum temperatures during seed ripening of the various cultivars are shown in Figs. 2 and 3. In 2010, the average and minimum temperatures were high in the early maturing stage and then decreased. In 2011, they increased in the early maturing stage and then remained almost constant. Sample seeds were collected from the plants that started flowering at about the same time in the two fields. Thus, the temperature conditions of the samples were similar in both fields.

2. Effects of soil moisture on the development, growth, yield, and quality of seeds

The data for plant growth in the two fields in 2010 and 2011 are listed in Tables 1 and 2. In the rotational paddy field, the flowering date tended to be later but the maturation date tended to be earlier than in the upland field. Thus, in the rotational paddy field the days to flowering tended to be longer but the days to maturing time tended to be shorter than in the upland field. Thus, the ripening period was shorter in the rotational paddy field than in the upland field. These responses were clearer in 2010. Plant height, stem length, and head diameter were significantly shorter in the rotational paddy field than in the upland field were observed in both 2010 and 2011. In 2011, the suppression of plant height and stem length on the rotational paddy field was severer than that in 2010. Leaf number was significantly smaller in the rotational paddy field in 2011, although there were significant differences in the leaf number of individual cultivars between the fields. Leaf N content in the rotational paddy field was significantly higher than that in the upland field before flowering, but significantly lower after flowering.

The yield and quality of seeds grown in the two fields are shown in Tables 3 and 4. In the rotational paddy field, 1000-kernel weight, seed and oil yields and oil content of seed were significantly lower than those in the upland field in 2010 and 2011 (Tables 3, 4). The oil concentration was significantly lower in the rotational paddy field only in 2010.
A significant difference in fatty acid components between the two fields was observed only in oleic acid in 2011, with the values being lower in the rotational paddy field.

3. Changes in seed quality, 1000-kernel weight, oil concentration, oil content, and fatty acid components during seed development

The temporal patterns of 1000-kernel weight during ripening are shown in Fig. 4. The 1000-kernel weight increased markedly from 14 to 25 d after initiation of flowering (DAF). There was little difference in 1000-kernel weight between the fields prior to 14 DAF, but afterward the difference became more apparent. The suppression of seed growth in the rotational paddy field began clearly around 25 DAF. The oil concentration and oil content also increased markedly from 14 to 25 DAF, and then these parameters increased gradually or remained stable, depending on the cultivars. Though there were no clear differences in oil concentration between the two fields during maturation, a clear difference in the oil content of seed was observed between the fields from about 25 DAF. Even with different sowing dates in 2010 and 2011, the oil accumulation in a seed in the rotational paddy field was suppressed similarly in both years. In 2010, the oil concentration of the seeds from the rotational paddy field was significantly lower than that in the upland field, and the oil content of a mature seed from the rotational paddy field was also significantly lower than that from the upland field (Figs. 5, 6, Table 3). In 2011, the oil content was significantly lower than that in the upland field though there was no significant difference in the oil concentration between the two fields (Figs. 5, 6, Table 4). The reduction in oil content of the seed from the rotational paddy field was almost parallel to the reduction in seed growth.

The fatty acid components of seeds at different maturation stages were also analyzed. In the mid-oleic hybrids (cultivars ‘Hysun511’, ‘63M80’, and ‘IS4704NS’), the oleic acid increased markedly until 14 to 25 DAF and

### Table 3. Yield and quality parameters of sunflower in the rotational paddy field in 2010.

| Field               | Cultivar             | 1000-kernel weight (g) | Yield (g plant−1) | Oil concentration (%) | Oil content (mg seed−1) | Oil yield (g plant−1) | Oleic acid (%) | Linoleic acid (%) |
|---------------------|----------------------|------------------------|-------------------|-----------------------|------------------------|----------------------|----------------|------------------|
| Rotational paddy field | Mid-Oleic F1 hybrid | 63M80                  | 41.7 abc           | 5.2                   | 34.5                   | 14.3 ab              | 2.6            | 62.0 a           | 24.7 c           |
| Rotational paddy field | IS4704NS             | 41.1 abc               | 3.0               | 27.3                   | 11.0 bc               | 0.9                  | 56.0 ab        | 30.6 bc          |
| Linoleic F1 hybrid   | Hybrid-sunflower      | 34.0 bc                | 14.6               | 33.3                   | 11.5 bc               | 5.2                  | 37.7 c          | 47.0 a           |
| Linoleic F1 hybrid   | North Queen           | 27.8 c                 | 5.4               | 28.1                   | 7.8 c                 | 1.5                  | 40.7 bc         | 45.2 ab          |
| Linoleic F1 hybrid   | Short stem            | 46.8 a                 | 9.2               | 29.7                   | 13.9 ab               | 4.8                  | 51.4 abc        | 35.9 abc         |
| Genetic resources    | Arm. 1)              | 59.1 a                 | 5.4               | 34.5                   | 20.4 a               | 1.9                  | 55.3 ab         | 32.1 bc          |
| Genetic resources    | Line41               | 50.9 ab                | 16.2              | 32.1                   | 16.4 ab               | 5.2                  | 46.8 abc        | 39.1 abc         |
| Upland field         | Mid-Oleic F1 hybrid  | 63M80                  | 55.8 ab           | 28.5                   | 42.0 a               | 23.6 ab             | 12.6           | 65.2 a           | 22.5 e           |
| Upland field         | IS4704NS             | 41.5 b                 | 24.1              | 39.4 ab               | 16.4 b               | 9.7                  | 59.0 b          | 27.9 d           |
| Linoleic F1 hybrid   | Hybrid-sunflower      | 48.1 b                 | 51.2              | 43.0 a               | 20.9 ab             | 22.8                  | 34.7d           | 52.2 a           |
| Linoleic F1 hybrid   | North Queen           | 44.7 b                 | 41.2              | 39.0 ab               | 17.4 ab             | 16.1                  | 43.1 c          | 44.6 bc          |
| Linoleic F1 hybrid   | Short stem            | 45.1 b                 | 16.7              | 33.5 b               | 15.1 bc             | 5.7                  | 45.4 c          | 42.0 bc          |
| Genetic resources    | Arm.                  | 67.8 a                 | 50.7              | 36.9 ab              | 28.8 a               | 18.5                 | 42.6 c          | 45.6 b           |
| Genetic resources    | Line41               | 69.5 a                 | 34.3              | 38.8 ab              | 27.0 a               | 13.2                 | 47.2 c          | 40.8 c           |
| Field               | *                     | **                     | **                 | **                     | **                   | ns                   | ns             |
| Cultivar            | **                     | ns                     | ns                 | **                     | ns                   | **                   | ns             |
| Field × Cultivar    | ns                    | ns                     | ns                 | ns                     | ns                   | ns                   | ns             |

1) Arm.: Armarvirskij3497.
* and **: significant at the 5% and 1% levels, respectively. Values followed by the same letter in a column are not significantly different at the 5% level by Tukey’s test.
reached their peak by about 30 DAF and then it remained stable in 2010 or decreased in 2011 (Fig. 7a, b). The linoleic acid components in the hybrids tended to be lowest at about 14 DAF and then showed an increasing trend (Fig. 8a, b). In the linoleic hybrids (‘North Queen’ and ‘Hybrid-sunflower’) the oleic acid increased from 10 to 14 DAF and then decreased (Fig. 7a, b). In contrast, the linoleic acid content in the hybrids firstly decreased and then they increased markedly from 14 to 25 DAF and then remained high (Fig. 8a, b). The temporal patterns of fatty acid components were similar in 2010 and 2011 (Figs. 7, 8).

Field × Cultivar | ** | ** | ns | ** | ** | * | ns
---|---|---|---|---|---|---|---
Field | * | * | * | * | * | ** | **
 Cultivar

Discussion

Soil moisture content is one of the major factors controlling the growth, yield and quality of sunflower, particularly when grown in a rotational paddy field or a field with poor drainage. In the rotational paddy field, the soil moisture conditions were high or changeable (Fig. 1), and the ripening periods of sunflower was shortened significantly (Tables 1, 2). The plant height, head diameter, leaf N content at flowering, 1000-kernel weight, oil yields, oil content in a seed and so on were also affected by high or changeable soil moisture conditions (Tables 1, 2, 3, 4). They were significantly lower or smaller in the rotational paddy field than in the upland field. The quality of sunflower seed such as oil concentration and the fatty acid components were also affected by high or changeable soil moisture conditions. The oil concentration and the oleic acid content were significantly lower in the rotational paddy field in 2010 and 2011, respectively (Tables 3, 4).
These results were similar to those reported by Yasumoto et al. (2011). In this study, we investigated also the changes in seed quality during seed ripening. Some effects of temperature condition on the seed quality have been reported. Robertson et al. (1978) found during seed development, that for each 1°C decrease in temperature, oleic acid decreased by 0.87% and linoleic acid increased by 0.32%. Martínez-Force et al. (1998) investigated the changes in fatty acid composition during maturation and the effects of temperature on normal fatty acid content in developing sunflower seeds. At 35 DAF, the linoleic/oleic acid ratio was lower in the seeds under the high-temperature condition (30/20°C day/night) than that under the low-temperature condition (20/10°C day/night). Izquierdo et al. (2006) reported that the critical period for oil fatty acid determination occurs between 100 and 300 ºCd (cumulative degree-days) after flowering (base temperature = 6°C). Gustavo et al. (2007) established a model to estimate the oleic acid and linoleic acid percentage as a function of mean minimum temperature between 100 and 300ºCd after anthesis (base temperature = 6°C). Sobrino et al. (2003) also reported that the temperature during development and maturation of sunflower achenes was the most important factor in the production of oleic acid. Considering such temperature effects, we sampled seeds that matured during the same period in the two fields with different soil moisture conditions to eliminate the effects of climatic differences. The oil concentration and oil content also increased markedly from 14 to 25 DAF (Figs. 5, 6). There was no clear difference in oil concentration between the two fields during maturation, but a clear difference was observed in the oil content. The difference in oil content of a seed between the fields was observed after about 25 DAF. The reduction of oil content in a seed from the rotational paddy field was parallel to the reduction of seed growth (Figs. 4, 6). Together these results indicate that the suppression of seed growth in the rotational paddy field due to higher or highly variable soil moisture contents was the major factor underlying the reduction in oil yield.

The temporal patterns of the fatty acid components during seed maturation were also examined in the different types of hybrids. The pattern varied with the cultivar. In mid-oleic hybrids, the oleic acid first increased markedly and then remained stable or decreased (Fig. 7). The content of linoleic acid in the hybrids first decreased and then increased (Fig. 8). In linoleic hybrids, the content of oleic acid first increased and then decreased (Fig. 7). The content of linoleic acid in the hybrids first decreased and then increased markedly (Fig. 8). Although the temporal patterns of fatty acid during seed maturation were similar in the two fields, the oleic acid content tended to be lower whereas the linoleic acid content tended to be higher in the rotational paddy field than in the upland field.

Several previous studies also investigated the changes in fatty acid composition during seed maturation in *H. annuus*. Robertson et al. (1978) found that during seed development, the percentage of linoleic acid increased until 56 DAF. Martínez-Force et al. (1998) investigated the changes in fatty acid composition during maturation. They found that the oleic acid content increased until 16 DAF and then decreased, whereas the linoleic acid content decreased until 16 DAF and then increased. Zlatanov et al. (2009) reported that the quantity of oleic acid in high oleic sunflower continued to increase gradually and the linoleic acid content also increased over time but generally remained low. The temporal changes in fatty acid composition have been said to be related to the activity of Δ-12 desaturase and Δ-15 desaturase (Rabiei et al., 2007). Lagravère et al. (2004) also suggested that the activity level of Δ-12 desaturase which affected on fatty acid desaturation
changed during the ripening period and resulted in changes in the fatty acid composition. The activity of Δ-12 desaturase is related to desaturation from oleic acid to linoleic acid. In the present study, the activity of the Δ-12 desaturase was thought to be changed over the course of the ripening period and to be different with the field.

Changes in the fatty acid composition in developing seeds have been reported for other crops as well. Ichihara and Noda (1980) studied the changes in developing safflower seeds, and found that linoleic acid predominated in every lipid class during seed development, while linolenic acid decreased with increasing maturation. Another study with safflower cultivars found that the contents of both saturated and unsaturated fatty acids fluctuated with seed growth and development (Rahamatalla et al., 2001). However, not many studies examined the changes in sunflower (Robertson et al., 1978; Zlatanov et al., 2009), much less the effects of high or changeable soil moisture conditions.

In Japan, sunflower cultivation in rotation with irrigated paddy rice or in farmland abandoned due to poor drainage has started to increase. The present study indicated the changes in the quality of seeds during seed maturation in the fields. The 1000-kernel weight, oil concentration and the content in a seed first increased markedly and then remained stable. The oleic acid content first increased and then tended to decrease in both mid-oleic and linoleic hybrids. The linoleic acid content first decreased and then tended to increase on both hybrids. Under similar temperature conditions, the above-mentioned changes in the 1000-kernel weight, oil content and the oleic acid content in the rotational paddy field tended to be lower than those in the upland field during the maturing period (Figs. 4, 6, 7). The differences between the fields were clear from around 25 DAF. As mentioned above, the fatty acid content is reported to be related to the activity of the Δ-12 desaturase and Δ-15 desaturase. The activity of Δ-15 desaturase is related to...
Changes in oleic acid content (%) during maturation in the two fields in 2010 (a) and 2011 (b).

rotational paddy field; upland field. Values and vertical bars are means and standard errors, respectively, of three to five plants.

Changes in linoleic acid content (%) during maturation in the two fields in 2010 (a) and 2011 (b).

rotational paddy field; upland field. Values and vertical bars are means and standard errors, respectively, of three to five plants.

desaturation from linoleic acid to linolenic acid. The activities of Δ-12 desaturase and Δ-15 desaturase were thought to be changed during the course of the ripening period and to be different also with the field. The present findings provide useful information for achieving high yields of seed and oil with the best fatty acid composition. Future research on the physiological mechanisms underlying the effects of excess soil moisture is necessary to increase seed yield and to improve seed quality.

Acknowledgments

We thank the staff members of the National Agricultural Research Center for their help in data collection.

References

Baydar, H. and Erbaş, S. 2005. Influence of seed development and seed position on oil, fatty acids and total tocopherol contents in sunflower (Helianthus annuus L.). Turk. J. Agric. For. 29: 179-186.

Berry, E.M. 1997. Dietary fatty acids in the management of diabetes mellitus. Am. J. Clin. Nutr. 66: 991s-997s.

Grassini, P., Indaco, G.V., Pereira, M.L., Hall A.J. and Trapani, N. 2007. Response to short-term waterlogging during grain filling in sunflower. Field Crops Res. 101: 352-363.

Gustavo, A.P. and Aguirrezábal, L.A.N. 2007. Sunflower yield and oil quality interactions and variability: Analysis through a simple simulation model. Agric. For. Meteorol. 143: 252-265.

Ichihara, K. and Noda, M. 1980. Fatty acid composition and lipid synthesis in developing safflower seeds. Phytochemistry 19: 493-494.

Izquierdo, N.G., Aguirrezabal, L.A.N., Andrade, E.H. and Cantarero, M.G. 2006. Modeling the response of fatty acid composition to temperature in a traditional sunflower hybrid. Agron. J. 98: 451-461.

Krajčovičová-Kudličková, M., Šimonič, R., Bederová, A. and Khrnová, J. 1997. Plasma fatty acid profile and alternative nutrition. Ann. Nutr. Metab. 41: 365-370.

Lagravère, T., Kleiber, D., Surel, O., Calmon, A., Bervillé, A. and Daydé, J. 2004. Comparison of fatty acid metabolism of two oleic and one conventional sunflower hybrids: A new hypothesis. J. Agon. Crop Sci. 190: 229-239.
Ma, J., Folsom, A.R., Lewis, L., and Eckfeldt, J.H. 1997. Relation of plasma phospholipid and cholesterol ester fatty acid composition of carotid artery intima-media thickness: The atherosclerosis risk in communities (ARIC) study. *Am. J. Clin. Nutr.* 65: 551-559.

Martínez-Force, E., Álvarez-Ortega, R., Cantisán, S. and Garcés, R. 1998. Fatty acid composition in developing high saturated sunflower (*Helianthus annuus*) seeds: Maturation changes and temperature effect. *J. Agric. Food Chem.* 46: 3577-3582.

Orchard, P.W. and Jessop, R.S. 1984. The response of sorghum and sunflower to short-term waterlogging. I. Effects of stage of development and duration of waterlogging on growth and yield. *Plant Soil* 81: 119-132.

Orchard, P.W., Jessop, R.S. and So, H.B. 1986. The response of sorghum and sunflower to short-term waterlogging. IV. Water and nutrient uptake effects. *Plant Soil* 91: 87-100.

Pendl, R., Bauer, M., Caviezel, R. and Schulthess, P. 1998. Determination of total fat in foods and feeds by the Caviezel method, based on a gas chromatographic technique. *J. AOAC Int.* 81: 907-917.

Rabiei, Z., Tahmasbei, E.S. and Vannozzi, G.P. 2007. Regulation of polyunsaturated fatty acids accumulation and characterization of linolenic acid after germination of sunflower seed. *Helia* 30: 175-182.

Rahamatalla, A.B., Babiker, E.E., Krishna, A.G. and El Tinay, A.H. 2001. Changes in fatty acids composition during seed growth and physicochemical characteristics of oil extracted from four safflower cultivars. *Plant Food. Hum. Nutr.* 56: 385-395.

Robertson, J.A., Chapman, G.W. and Wilson, R.L. 1978. Relation of days after flowering to chemical composition and physiological maturity of sunflower seed. *J. Am. Oil Chem. Soc.* 55: 266-269.

Sobrino, E., Tarquis, A.M. and Diaz, M.C. 2003. Modeling the oleic acid content in sunflower oil. *Agron. J.* 95: 329-334.

Yasumoto, S., Terakado, Y., Matsuzaki, M. and Okada, K. 2011. Effects of high water table and short-term flooding on growth, yield, and seed quality of sunflower. *Plant Prod. Sci.* 14: 233-248.

Zlatanov, M.D., Angelova-Romova, M.J., Antova, G.A., Dimitrova, R.D., Momchilova, S.M. and Nikolova-Damyanova, B.M. 2009. Variations in fatty acids, phospholipids and sterols during the seed development of a high oleic sunflower variety. *J. Am. Oil Chem. Soc.* 86: 867-875.