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Effects of Ridge Width on the Growth and Yield of Foxtail Millet (*Setaria italica* (L.) P. Beauvois) in Paddy-Upland Rotation Fields

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Abstract

Rice cropping areas have recently been restricted or reduced under the policy of the South Korean government. Therefore, the development of new crop or cropping systems is essential. Foxtail millet (*Setaria italica*.) is considered among the best candidate crops to substitute for rice, but there is limited information about maintaining or improving the grain yield without crop damage caused by excessive water content in sandy paddy fields. A two-year study from 2013 to 2014 was conducted in a trial field in the southern part of Korea (N 35° 05′ 16.8″, E 127° 56′ 34.6″). The three cultivars selected—Gyeongkwan 1, Samdachal, and Hwanggeumchal—are the most common varieties of foxtail millet in South Korea due to their highly functional nutrients and potential productivity. For the purpose of establishing the stable production of Foxtail millet in paddy-upland rotation fields, the effects of ridge width (60, 120 and 240 cm) on soil moisture in the ridge, and on the growth and yield of foxtail millet were investigated in a sandy paddy field. Soil water content increased in line with increasing ridge width. Therefore, the estimated retention time of excessive soil water during the cultivation period tended to increase in line with increasing ridge width. Foxtail millet plants reached the highest level of height in the 60-cm ridge width treatment in both years of the study. The grain yields in 2014 were 3.44, 3.77, and 3.28 tons·ha^{-1} for Gyeongkwan 1, Samdachal, and Hwanggeumchal, respectively, grown in the 60-cm ridge width. The plant height and yield of foxtail millet had increased with a narrowed ridge width because soil-moisture conditions are remedied by ridge width. Therefore, we recommend that a ridge width of 60 cm be maintained to prevent excessive water damage to foxtail millet growth in a sandy paddy field.

Discipline: Crop production
Additional key words: Excessive moisture, retention of excess water, yield components

Introduction

Foxtail millet (*Setaria italica* (L.) P. Beauvois) is a monocotyledon poales of gramineae, an annual plant that is native to most of East and Central Asia (Yu & Wu 1996, Ha & Lee 2001), and grown in Korea, Japan, India, Central Asia, Southern Europe, North Africa, and the USA (Yoon & Xu 2008).

Recent years have witnessed a growing interest in health and wellness, as both the quality of life and economic growth have improved. In particular, the high nutritive values of foxtail millet among cereals have led to a gradual growth in demand for this plant (Sung & Kwon 2011).

In Korea, however, common crop and soil management practices for foxtail millet have yet to be established and standardized. This is mainly because Korean agriculture is dominated by rice and research on developing cultivation methods for other grains is relatively limited (Kang 2010).

The ratio of rice cultivation area to all cropland is pre-determined by law in South Korea, whereby the total land available for crop production tends to decrease (Kwon 1993). Therefore, in order to comply with the

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policy of reducing the rice cultivation area and improving farmers' income, a new economically viable crop should be introduced instead of rice. Hence, economically viable crops such as foxtail millet are considered highly functional crops, and foxtail millet is considered the best crop for satisfying both requirements. Along with various changes in the paddy cropping systems, there is also a need to develop new techniques for any new crop introduced to the rotation with rice (Kim et al. 1995, Kim et al. 1993).

Some benefits of farming practices based on paddy-upland rotation include improvements in soil chemical properties, the mitigation and prevention of disease and pest problems, evasion of successive cases of crop injury, reduction of weed infections, and an increase in productivity per unit area (Lee 1988). Growing crops other than rice in paddy fields requires adjustments to system management, but soil conditions may potentially induce physiological stresses due mainly to poor soil drainage. This is especially the case for upland paddy soils, where it is difficult to eliminate surface runoff water. Another potential problem is caused by excessive amounts of rain, resulting in paddy soil absorbing and retaining excessive amounts of moisture in the root zone of soil. Water is an important factor that affects the emergence of seedlings and early growth of crops (Devane 2009, Jabbari et al. 2013). The growth and development of crops with shallow roots could be limited or even fail under such high soil moisture conditions; consequently, such crops are prone to root injury due to freezing or drought (Yun et al. 2009).

Foxtail millet is a crop characterized by shallow roots; as such, it requires less water and is thus more susceptible to damage by excess water in the soil (Cho et al. 2010, in Korean). The ridge width is generally 240 cm in farmers' fields due to its convenience in reducing the number of ridges as compared with a narrower ridge width. However, such a width has resulted in several problems. One problem is excess water damage after heavy rainfall in clayey soils, which results in uneven ripening dates and damage to a low percentage of plants planted in the mid-row of a bed. Therefore, cultivation methods should be established and standardized in paddy fields to maintain annual productivity. The problem is mostly the mid- or central point of a ridge. However, excess water damage poses no problem in the near furrows, and thus there is an urgent need to conduct ridge width experiments. Up until now, most studies have focused on rice, but virtually no study has investigated the growth and development of useful crops in paddy-upland rotation. Research on foxtail millet growing methods is also virtually nonexistent in Korea. Information is needed to determine what is required for the stable production of foxtail millet, based on its growth characteristics by ridge widths, changes in soil chemical characteristics, and the moisture status in paddy-upland rotation cropping systems. Therefore, we conducted a field experiment from 2013 to 2014 to compare the effects of varying ridge widths on the growth and productivity of foxtail millet (Gyeongkwan 1, Samdachal, and Hwanggeumchal).

Materials and Methods

1. Experimental site

Our study was conducted in an on-farm trial field that had been used for almost 30 years for continuous rice cultivation, and which is located about 100 m from a small river. Characterized by a high underground water level, the site is surrounded by paddy fields. Therefore, water penetration is naturally lower than that upland, which is very common in Korea. The site is located in the Sacheon area of Gyeongnam, Korea (N 35° 05' 16.8", E 127° 56' 34.6"). The soil had a moderately coarse texture. Table 1 lists the soil chemical characteristics of the experimental field.

2. Treatment methods

The effects of three different ridge widths (60, 120 and 240 cm) on a drained paddy field were compared. The experimental design was a randomized block with three

Table 1. Chemical properties of soil before the experiment in 2013 and after harvesting in 2013 and 2014

Year	Soil Depth	pH	EC	O.M.	T-N	Avail. P_2O_5	Exch. cation			
							K	Ca	Mg	Na
	cm	(1:5)	ds m^{-1}	g kg^{-1}	%	mg kg^{-1}	……… cmol kg^{-1} ………			
Before experiment		5.1	0.28	15.3	0.21	143	0.15	2.3	0.45	0.04
2013	Ap1 (0-14)	5.4	0.27	16.6	0.21	127	0.12	3.39	0.64	0.03
	2C (15-24)	5.3	0.21	15.4	0.2	108	0.08	3.22	0.59	0.05
2014	Ap1 (0-14)	5.5	0.28	19.2	0.17	510	0.13	3.05	0.6	0.06
	2C (15-24)	5.6	0.24	20.4	0.15	427	0.1	3.15	0.5	0.06

replications. The size of each plot was 100 m^2. This experiment was conducted over a period of two years (from 2013 to 2014), with the planting time typically in June and the harvesting time in September. The cultivation methods used in the experimental field were: 1) application of fertilizer consisting of urea, fused phosphate, and potassium chloride to the soil surface at the rate of 9 kg of nitrogen, 7 kg of phosphorus, and 8 kg of potassium per 10 ha, 2) cultivation by tractor with a soil depth of 15 cm, 3) use of a small tractor after harvest to form ridges by making ditches (30 cm in width, 30 cm in depth) at intervals of 60, 120, and 240 cm, 4) use of plastic black film to cover the ridges, and 5) transplanting two-week old seedlings with an inter-row spacing of 60 cm and intra-row spacing of 10 cm on June 18, 2013 and June 19, 2014. Three foxtail millet cultivars—Gyeongkwan 1, Samdachal, and Hwanggeumchal—were selected and evaluated in this study, mainly because these cultivars are the most popular in terms of supporting good scenery, being a sticky grain, and offering high functionality.

3. Soil moisture measurements

In this experiment, soil characteristics were investigated in bulk soil up to 24 cm in depth before the experiment, but the soil was divided into two soil layers: Ap1 (0-14 cm) and 2C (15-24 cm). Soil moisture content was measured by a soil moisture sensor (SMEC 100, Spectrum Technologies, Inc. USA) at each plot during the growing season. The sensor was installed at a depth of 30 cm in the middle part between rows near the center of the ridge for each plot after planting in 2013 and 2014. However, the sensor was installed at a depth of about 20 cm at harvest because soil compaction during the cultivation period had changed the soil bulk density from 0.8 $g{\cdot}cm^{-3}$ to 1.2 $g{\cdot}cm^{-3}$. The soil moisture content measurements were recorded every hour with a data logger (WatchDog 1000-Series, Spectrum Technologies, Inc. USA), and the data was analyzed as the mean of three replications in both years (Fig. 3).

The chemical analysis of soil was conducted according to the method of soil and plant analysis (NIAST 2000) specified by the Rural Development of Administration, and tests on soil properties such as soil texture were carried out according to the Agronomical Survey Standard (USDA 1996).

4. Estimation of retention time of excessive soil water

The average sum of excess water table depth above 30 cm (SEW30) was discussed by Darzi-Naftchally et al. (2014). It was originally defined by Sieben (1964) to evaluate the influence of highly fluctuating water levels on cereal crops in winter. The SEW-30 measurements were done at the 30-cm depth, equivalent to the furrow depth. It was used herein to quantify excessive soil water conditions during the growing season and calculated as:

$$\text{SEW-30} = \sum_{i=1}^{n} (30 - xi)$$

(In the thesis, *xi* is the water table depth below the ground surface in cm, *i* is one day, and *n* is the number of days in the growing season.)

5. Characteristics of plant growth and grain yield

Twenty-five days after transplanting in the experimental field, the height of 10 plants was surveyed at the midpoint and center of the bed, except for the two outside rows. The yield of foxtail millet grown in an area of 3.3 m2 (1.8 m x 1.8 m) was investigated, thereby cutting the regular growth and development point at harvest time. The ear length was tested and each 500 g sample was dried at 75°C in a grain circulating type of natural air in-bin dryer for 48 hours; the measurements covered 1) 1000-seed weight, 2) seed weight per ear, and 3) grain yield per ha.

The mean value of the collected data was compared as per the PROC ANOVA procedure of the SAS program (V. 9.2, Cary, NC, USA), through Duncan's multiple range test (DMRT), with a significance level of 5%.

Results

1. Weather characteristics of the study site

Figure 1 shows rainfall in the region during the cultivation period. The total rainfall in 2013 was recorded as 581 mm, much less than the annual average of 990 mm (1981-2010). Rainfall during the cultivation period was concentrated from the end of June through the first part of July. The total rainfall in 2014 was recorded as 1,029 mm, exceeding the annual average rainfall and resulting in a total of 59 rainy days from the middle of June to the later part of July. The last ten days of August also showed high rainfall; the highest rainfall of the year (at 94.5 mm) was recorded on August 3rd. There was also exceptionally heavy rainfall in September and October 2014, resulting from typhoons FUNG-WONG and VONGFONG, respectively.

2. Soil characteristics

Table 1 lists the chemical characteristics of the soil before and after cultivation. Before the experiment, the characteristics of the experimental sandy soil (mainly located on the near side of a river or stream) were those of typical sandy paddy soil, similar to more than 50% of Korean sandy paddy soil (Jung et al. 1982), with a little lower pH of 5.1. The organic matter was 15.3 $g{\cdot}kg^{-1}$, Ca was 2.30, and Mg was 0.45 $cmolc{\cdot}kg^{-1}$ (or levels a little lower than those for typical Korean paddy soil). After the first year of the experiment, the pH of the topsoil increased slightly to 5.4, but available phosphorus in both the topsoil and subsoil layers decreased slightly to reach 16 and

35 mg·kg^{-1}, respectively, compared to the prior experiment. However, Ca content was 1 cmolc·kg^{-1}, which was higher than in the prior experiment. In the second year, the soil pH increased slightly higher than that in the first year, with 5.6 in the subsoil, and organic matter content increased to 20.4 g·kg^{-1} in the subsoil compared to the first year. While the total soil nitrogen content was 0.21 in topsoil before the experiment, it decreased to 0.15 after the experiment in 2014. The available soil phosphate content was greatly increased from 143 mg·kg^{-1} before the experiment and reached 510 mg·kg^{-1} after the experiment. After the two experiments, the increases in organic matter and phosphoric acid were considered due to the accumulation of crop residue by millet continuous cropping.

3. Soil moisture characteristics

Figure 2 shows the investigation of soil moisture characteristics by ridge width. The figure showed July 26th in 2013 and August 7th in 2014 as the days with highest moisture content after a heavy rain, accounting for 50.7% and 50.0%, respectively, at a soil depth of 30 cm in all ridge width treatments. In 2013, the soil moisture decreased two days after that to 34.3%, 27.5%, and 22.1% in the 240-cm, 120-cm, and 60-cm plots, respectively. In 2014, the moisture content decreased to 29.8%, 23.2%, and 18.0% in the 240-cm, 120-cm, and 60-cm plots, respectively. In 2013, by August 9th, two weeks later, the highest soil moisture content was recorded in the 240-cm plot at 26.8%, while it was 8.57% in the 60-cm plot, or 41.3% lower than the content recorded on the initial day of saturation. In 2014, by August 18th, 10 days later, the highest soil moisture content was recorded in the 240-cm plot at 29.8%, while it was 18.5% in the 60-cm plot, or 31.5% lower than the content recorded on the initial day of saturation. Therefore, among all plots, the change in moisture content of the soil was highest in the 60-cm plot, which suggests that the narrowest plot was better suited for the drainage of excess water.

The critical point of the excess moisture condition was indicated as 30% at the 30-cm soil layer, which is called SEW-30 (Darzi-Naftchally et al. 2014); however, it could be different based on the soil texture and infiltration rate, which were evaluated with a focus on excessive moisture content. This phenomenon of excess water in the soil leads to oxygen deficiency and root decay, and also results in

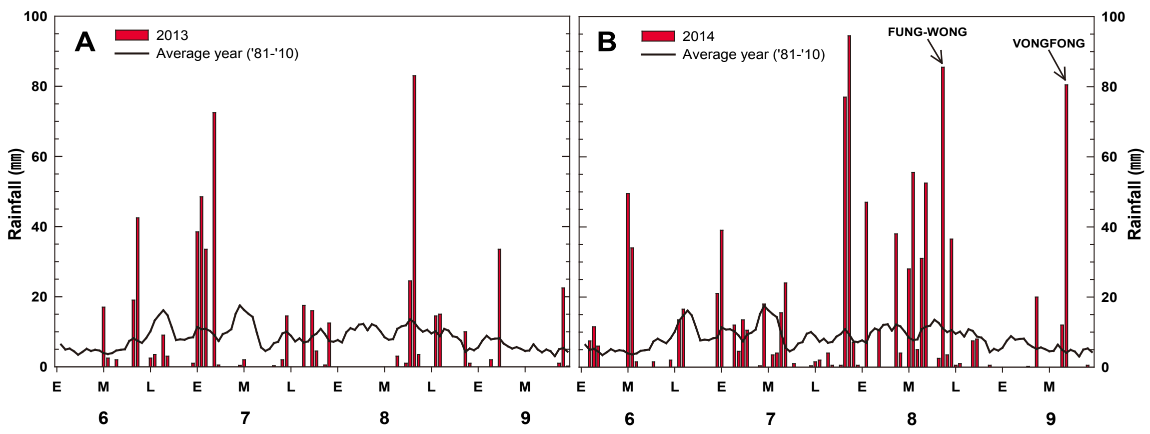

Fig. 1. Amount of rainfall in 2013, 2014, and average year (1981-2013) at the experimental field (A: 2013; B: 2014).

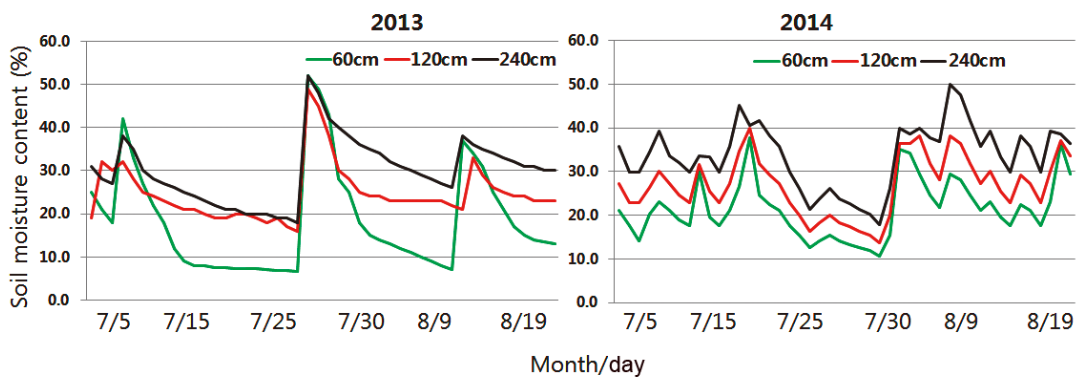

Fig. 2. Soil moisture content by ridge width in foxtail millet plots (in 2013 and 2014).

etiolation chlorosis of the top part of plants, which is called wilting or withering. This problem commonly occurs in barley cultivated in a barley-rice double cropping system in paddy fields without open ditches, and is also more serious in vegetables in flooded areas (Chae et al. 2012). According to Wesseling (1974), soil pores become saturated with moisture when excessive moisture levels occur in farmlands with poor drainage, which leads to the occurrence of noxious substances by soil incorporation, limits the healthy activity of microorganisms in the soil, and causes crop stress. The oxygen supply can be restored by draining water or shortening the duration of crop exposure to excessive water in order to prevent excess water damage.

Figure 3 shows the sum of times of excess water over 30% by ridge width in foxtail millet. The retention of excess water in the soil during the cultivation period causes excess moisture injury that is closely correlated with ridge width. The retention time of more than 30% of the soil moisture content was 1,006 hours in the 240-cm ridge width plot, compared to 255 hours in the 60-cm ridge width plot, for a difference of 740 hours. These results explain that the shallow-rooting foxtail millet, which is the weakest against excessive water content, might be damaged by more than 40 days of retention. This might cause a huge effect on the growth and development of the plant (Cho et al. 2010).

4. Growth characteristics

The plant height of the three tested cultivars was evaluated based on ridge width, and was found to decrease in line with increased ridge width (Fig. 4). Gyeongkwan 1 was the highest (82.0 cm and 83.8 cm) when grown in the 60-cm ridge width, while it was 70.3 cm and 70.2 cm in the 240-cm ridge width in both the 2013 and 2014 experiments, respectively. For the Samdachal cultivar, the plant height

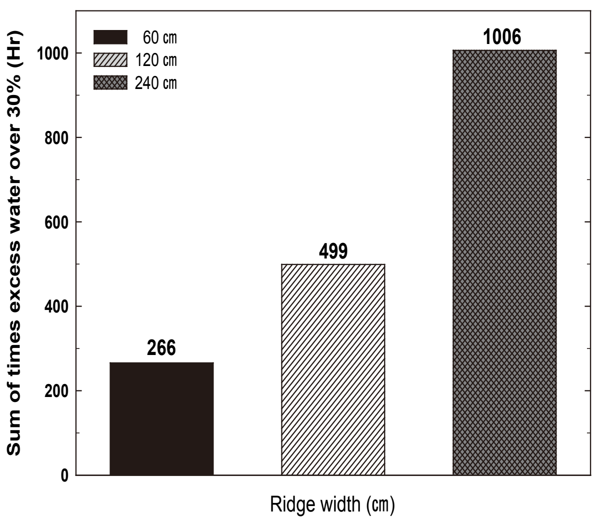

Fig. 3. Sum of times of excess water over 30% by ridge width in foxtail millet.

was 88.0 cm and 86.0 cm in the 60-cm ridge width, and it decreased to 56.8 cm and 72.0 cm in the 240-cm ridge width in both the 2013 and 2014 experiments, respectively. For the Hwanggeumchal cultivar, the plant height was 73.6 cm and 87.3 cm when grown in the 60-cm ridge width, but it decreased to 43.8 cm and 70.0 cm in the 240-cm ridge width in both years (2013-2014). In conclusion, the foxtail millet plant height decreased in all cultivars when the ridge width was increased.

5. Yield components and grain yield

In the first year, the ear length of the three foxtail cultivars tested decreased in line with increasing ridge width without any statistical significance (Table 2). However, in the second year, significant differences were found in Gyeongkwan 1 and Samdachal cultivars with ear lengths of 25.8 cm and 26.1 cm, respectively, when grown in the 60-cm ridge width plot. On the other hand, both were greatly reduced to ear lengths of 24.0 cm and 23.4 cm in the 240-cm ridge width and not significantly different from those grown in the 120-cm ridge width plot.

In 2013, grain weight per ear did not differ among the ridge width treatments, but was significantly different in 2014 when Hwanggeumchal had the heaviest grain weight of 28.1 g in the 60-cm ridge width plot.

The 1000-seed weight was significantly different in Samdachal among the different ridge width treatments, and was 4.07 g and 5.61 g in the 60-cm ridge width, but was 3.58 g and 5.20 g in the 240-cm ridge width in 2013 and 2014, respectively. The 1000-seed weight was not significantly different in the other two cultivars in both years. The same statistical analyzing methods were used for the yield components, but there was a great difference in yield components and grain yield attributed to significantly improved weather conditions.

The grain yield was significantly different among the cultivars and ridge width treatments in both years (Fig. 5). In 2013, Gyeongkwan 1 yielded 2.21 tons, Samdachal 2.23 tons, and Hwanggeumchal 2.25 tons per ha in the 60-cm ridge width plot, while Gyeongkwan 1 yielded 2.07 tons, Samdachal 2.12 tons, and Hwanggeumchal 2.07 tons per ha in the 240-cm ridge width plot. In the 2nd year, the grain yield was very similar to that in 2013 at 3.44 tons, 3.77 tons, and 3.28 tons per ha in Gyeongkwan 1, Samdachal, and Hwanggeumchal in the 60-cm ridge width plot, respectively, but was 3.00 tons, 3.39 tons, and 2.23 tons per ha in Gyeongkwan 1, Samdachal, and Hwanggeumchal in the 240-cm ridge width plot, respectively. When converted into a percentage, the gain yield showed 12.8%, 10.1%, and 32.0% of the grain yield loss in Gyeongkwan 1, Samdachal, and Hwanggeumchal due to the increased ridge width from 60 to 240 cm.

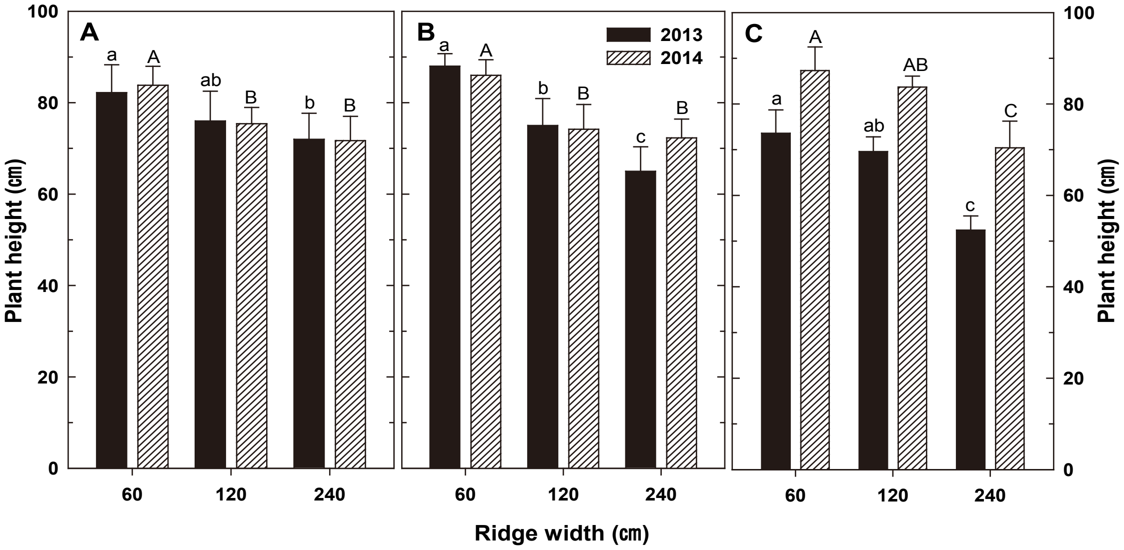

Fig. 4. Plant height of foxtail millet as affected by ridge width at 40 days after seeding.
(A: Gyeongkwan 1; B: Samdachal; C: Hwanggeumchal). Mean values with different superscript lowercase letters of the same cultivated times are significantly different as per Duncan's multiple ranged test ($p < 0.05$). Mean values with different superscript uppercase letters at one variety are significantly different as per Duncan's multiple ranged test ($p < 0.05$).

Table 2. Grain yield components as affected by ridge width in foxtail millet cropped in a drained paddy field

Cultivar	Ridge width	Ear length		Seed weight per ear		1000-seed weight	
		1st year	2nd year	1st year	2nd year	1st year	2nd year
	cm	……… cm ………		……………………… g ………………………			
GK1[1)]	60	21.3[a2)]	25.8[a]	14.9[a]	26.9[a]	3.80[a]	6.89[a]
	120	21.2[a]	24.4[a]	13.3[a]	24.5[b]	3.66[a]	6.69[a]
	240	21.0[a]	24.4[b]	13.3[a]	19.6[c]	3.55[a]	5.92[a]
SDC	60	18.8[a]	26.1[a]	11.9[a]	20.0[a]	4.07[a]	5.61[a]
	120	17.0[a]	25.4[b]	11.2[a]	18.6[b]	3.73[b]	5.54[b]
	240	16.9[a]	23.4[b]	10.6[a]	16.8[b]	3.58[b]	5.20[c]
HGC	60	21.0[a]	22.8[a]	17.9[a]	28.1[a]	4.13[a]	6.75[a]
	120	21.0[a]	22.7[a]	17.0[a]	18.2[b]	3.73[a]	6.35[a]
	240	19.9[a]	21.2[a]	11.9[b]	15.1[b]	3.36[a]	6.07[a]

1) GK1: Gyeongkwan 1; SDC: Samdachal; HGC: Hwanggeumchal

2) Mean values with different superscript lowercase letters of the same cultivated times are significantly different as per Duncan's multiple ranged test ($p < 0.05$).

Discussion

This research was conducted to determine the best ridge width for the prevention of excess water damage, and to maintain and increase the grain productivity of foxtail millet in sandy soil by investigating the characteristics of crop growth and yield, the chemical properties of soil, and soil moisture in drained-paddy fields.

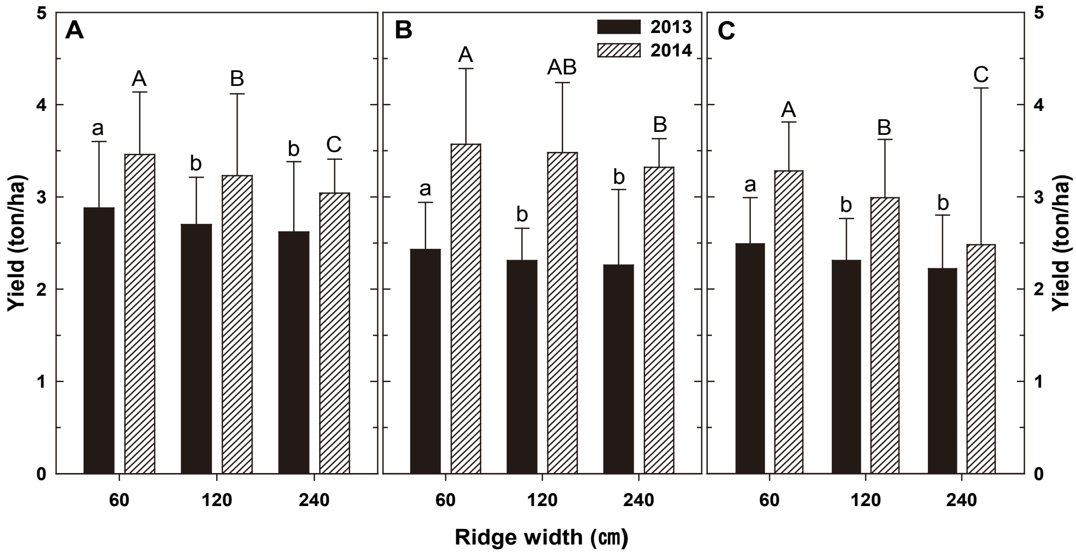

Fig. 5. Grain yield as affected by ridge width in foxtail millet (A: Gyeongkwan 1; B: Samdachal; C: Hwang-geumchal).
Mean values with different superscript lowercase letters of the same cultivated times are significantly different as per Duncan's multiple ranged test ($p < 0.05$). Mean values with different superscript uppercase letters at one variety are significantly different as per Duncan's multiple ranged test ($p < 0.05$).

The grain yield increased significantly in line with decreasing ridge width from 240 cm, 120 cm, to 60 cm; the yield increases were closely related to the improved drainage of excessive soil water (Fig. 2, Fig. 5). In particular, we also measured that the maximum water content after a heavy rain was 50.7% (VWC,%) and then decreased to 8.57% after 14 days in the 60-cm ridge width in sandy soil, while it was 24.9% in the 240-cm ridge width. Therefore, there were differences in water retention time by ridge width. Past studies have shown that the increase in soil-water retention time might be negatively related to crop growth, such as plant height and ear weight, as also shown in this study (Kim, T. Y. 2013, Fig. 2, Table 2). Excessive soil water content presumably led to reduced plant height, and more excessive water damage would be expected by increasing ridge widths even in sandy soil located by the side of a paddy field. The number of ears per plant did not differ significantly among the ridge width treatments; however, ear length was related to the number of seeds per ear, which was closely related to the grain yield, and the narrowed ridge width reduced excessive water damage. Moreover, increased photosynthesis may have resulted due to the avoidance of excess water damage and also contributed to increased ear size that was related to the grain number and yield.

In general, plant density can be reduced by decreasing the ridge width as the number of furrows per given area increases. In our study, however, the row distance of foxtail millet in the 60-cm plot was similar to that of the 240-cm ridge width. Conversely, there could be some increases in labor cost by increasing the number of furrows, but such increases would be offset by reducing yield losses. There were serious losses of grain yield by 5.84% and 18.3% in 2013 and 2014, respectively, and the yield loss was highest (at 32%) in Hwanggeumchal. This experimental area was located in the center of a paddy field and the ground water depth was 40 cm—a soil characteristic common in Korean paddy fields that inhibits water penetration. Moisture escapes from macro-pores and air commonly replaces that space. As shown in Fig. 2, the soil moisture content fluctuated due to heavy rain and was not influenced by the soil moisture curve in sandy soil, because the high underground water level reduced water penetration, yet excessive water was decreased by ridge width. When the ridge width was wider, micro-pores or capillary pores remain filled with moisture longer, the moisture is absorbed by soil particles, and the length of time that moisture stays in the soil is increased (Nyle & Ray 2010). Thus, foxtail millet is considered particularly vulnerable in paddy soils with wider ridge widths.

The intake of gas and moisture are thus affected, which in turn decreases the photosynthetic rate, coupled with a decrease in transpiration and water use efficiency, which ultimately leads to a decline in yield (Boyer 1970, Bennet & Albrecht 1984). In this way, the soil moisture content as a result of ridge width significantly affects the yield, particularly for foxtail millet (Cho et al. 2010), which is extremely vulnerable when it comes to injury caused by excess water. It is thus advantageous to grow foxtail millet in plots with ridge widths of 60 cm in paddy-upland rotation fields. A more detailed study is needed on the different physical and chemical properties of soil, and on the characteristics of moisture transport in the soil of paddy-upland rotation fields.

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