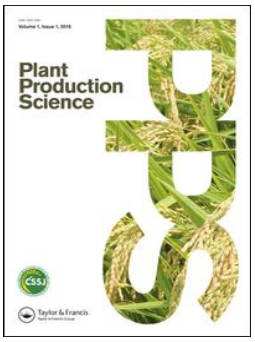

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Genetic Resources and Evaluation

Comparison of Growth and Yield Performance of Several Water Chestnut Species Collected from Southwestern Japan and Middle China

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Abstract : Vegetative growth characters and yield components of water chestnuts distributed in Japan and China were investigated for 12 local lines of 6 species ; i.e., 5 small and 2 medium fruit lines from Japan, and 5 large fruit lines from China. The materials were transplanted and grown in a flooded field usually used for rice cultivation in Saga City in 1995. The lines from China had higher rates of foliage formation, developed emersed leaves earlier and maintained them longer compared with the Japanese lines. The small fruit lines of Japan had the shortest growing period, although the number of rosettes was larger. The fruit yield of the small, medium and large fruit lines, was 250 to 400 g m^{-2}, about 600 g m^{-2} and 600 to 1,000 g m^{-2} , respectively. The fresh weight of well-ripened fruit was 1 to 5 g for the small fruit lines, 5 to 10 g for the medium fruit lines and more than 10 g for the large fruit lines. The number of fruits per m^2 increased as the fruit size of the lines decreased. However, the productivity of the water chestnut was higher in the large fruit lines than in the small or medium fruit lines.

Key words : Aquatic plant, Paddy field cropping, *Trapa*, Water chestnut, Yield.

Water chestnut (*Trapa* sp.) is the only floating annual plant which produces fruit in a freshwater environment. It germinates at the bottom of the water at the end of spring, and extends many branching stems to the surface of the water and develops floating leaves like a rosette at each stem apex. This plant is a minor but popular aquatic plant distributed in various parts of the world. It is also a very useful plant, because shallow fresh waters can be used for food production. In India, China and Italy, economical production has been carried out in water areas on low and flat lands or lakes (Daniel et al., 1983 ; Kumar et al., 1985 ; Kusum and Chandra, 1980 ; Mazumdar, 1985 ; Srivastava and Tandon, 1951). In many countries in the torrid and temperate zones, people eat the fruit of native stock as grain and the stem and leaves as vegetables. Recently, however, it is rarely utilized and is sometimes treated as a weed in some countries because of its vigorous propagation resulting from eutrophication of fresh water areas (Smith, 1955 ; Brezny et al., 1973 ; Methe et al., 1993 ; Groth et al., 1996).

In Japan, the water chestnut is naturally distributed throughout the country and its fruits are harvested and consumed. Because of the intensified rice acreage restriction program, the water chestnut has been introduced into some areas as an alternative crop for rice on paddy fields. It is possible to grow water chestnut in a labor-saving way, and to maintain a good paddy field ecosystem at the same time. Maintaining a good paddy field ecosystem is desirable for many reasons, including flood prevention, cultivation of underground water, and prevention of the expansion of nitrate nitrogen pollution.

Until the present, studies on the water chestnut have been carried out mainly in the field of botany, and thus, its varietal characteristics and cultivation methods have been largely ignored. We have already reported on the growth and yield performance of the water chestnut, *Trapa bispinosa* Roxb. (Arima et al., 1990, 1992a, 1992b, 1992c, 1992d, 1993). In the present series of experiments, we have aimed at establishing a high yielding culture method by elucidating the physiology and ecology of the water chestnut, and at the same time, are striving to obtain basic data for improving productivity. In this experiment, with several varieties of temperate-zone water chestnut grown in the paddy field by transplanting culture was collected from the central part of China and Kyushu in Japan, and their vegetative growth characteristics and yield were analyzed.

Materials and Methods

Five lines with small fruit (*Trapa japonica* Flerov) and 2 lines with medium-sized fruit (*T. natans* L. var *quadrispinosa* Makino, *T. natans* L. var *rubeola* Makino) grown in Japan and 2 lines with large fruit (*T. bispinosa* Roxb.) and 3 other lines with large fruit (*T. quadrispinosa* Roxb., *T. bicornis* L., *T. acornis* Nakano.) grown in China, a total of 12 lines of 6 species (Table 1), were used in this investigation. Water chestnut was cultivated in a 6- are (20 m×30 m) paddy field at the Faculty of Agriculture, Saga University (situated at 34° N). The changes of air

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Table 1. Materials.

Line	Scientific name	Collecton site[1)]	Fresh weight of seed[2)] (g)	Shape of fruit: Size[3)]	Shape of fruit: No. of spines[4)]
1	*Trapa bispinosa* Roxb.	China (Shanghai)	30.0	L L	2
2	*T. quadrispinosa* Roxb.	China (Hangzhou)	27.0	L L	4
3	*T. bicornis* L.	China (Shanghai)	20.0	L L	2
4	*T. bispinosa* Roxb.	China (Hangzhou)	16.0	L	2
5	*T. acornis* L.	China (Hangzhou)	15.0	L	0
6	*T. natans* L. var. *quadrispinosa* Makino	Japan (Fukuoka)	8.0	M	4
7	*T. natans* L. var. *rubeola* Makino	Japan (Nakanotate)	6.0	M	4
8	*T. japonica* Flerov	Japan (Kubota)	2.5	S	2
9	*T. japonica* Flerov	Japan (Kawasoe)	2.5	S	2
10	*T. japonica* Flerov	Japan (Kase)	2.1	S	2
11	*T. japonica* Flerov	Japan (Nisiyoga)	1.7	S	2
12	*T. japonica* Flerov	Japan (Kose)	1.6	S	2

1) No. 7～No. 12 were collected in the Saga plains of Kyushu.
2) Standard weight of big size fruits used for raising seedlings of each line.
3) The size was decided by the fresh weight of fruit : LL, over 20 g ; L, 10～20 g ; M, 5～10 g ; S, below 5 g.
4) No. of spines is the eigen value for each line.

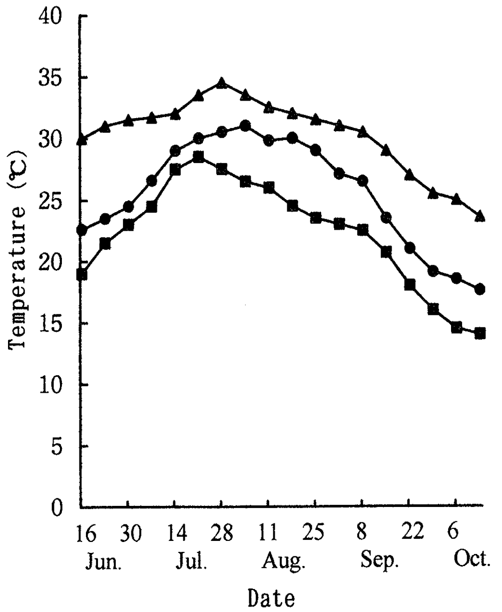

Fig. 1. Seasonal changes in air and water temperatures.
●, Mean air temp, ; ■, Min. water temp, ; ▲, Max. water temp.
Water temperature was measured 5 cm below the water surface.

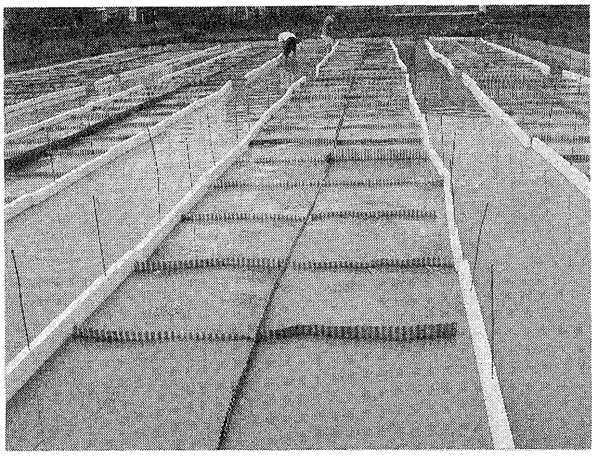

Fig. 2. Experimental field.
In a paddy field, 144 experimental plots were partitioned by plastic board. Styrene foam was floated in one side of each plot to circulate water. Water depth was kept at about 15 cm.

and water temperature during the growing season are shown in Fig. 1. Prior to transplanting, the paddy field was plowed, fertilized, puddled, levelled, and then supplied with underground water to maintain a water depth of about 15 cm. The fields were divided by corrugated plastic sheets into 144 1 m×1 m (12 lines×12 replications) plots. Polystyrene foam was floated along one side of each plot so that irrigation water could circulate within the experimental plot (Fig. 2). The seeds harvested in 1994 were sown in water tanks on April 1, 1995. Uniformly grown 50-cm-long segments of each branch stem were cut from the stock plants and used as seedlings. One seedling was transplanted on June 7, 1995 into each plot. N, P_2O_5 and K_2O were applied as a basal dressing by using slow release compound fertilizers at the rate of 3 kg, 3.4 kg and 3 kg per 10 a, respectively. Butylphenyl methylcarbamate emulsifiable concentrate was sprayed once against an attack of leaf beetles. Weeds were removed by hand.

The number of leaves emerged per day was examined with 20 rosettes. The rosette number per m^2 and the percentage of water surface covered (% covered) with floating leaves and emersed leaves were measured at one-week intervals. After the completion of emersed leaf foliation, the maximum diameter and the emersed height of 15 rosettes of each type were measured on 5 Sept. The dry weight of each organ and leaf area per m^2 were measured for 4 plants per line. The percentage of water surface covered with emersed and floating leaves was observed on 2 Oct. The green levels of 3 leaves developing on the 7th, 8th and 9th nodal positions of branches were measured on 4 Aug. and 2 Oct. for 20 stems in each plot with a greenmeter (CT101, Fujihira Co.).

Fruits were harvested on 20 Oct. from 7 plots with

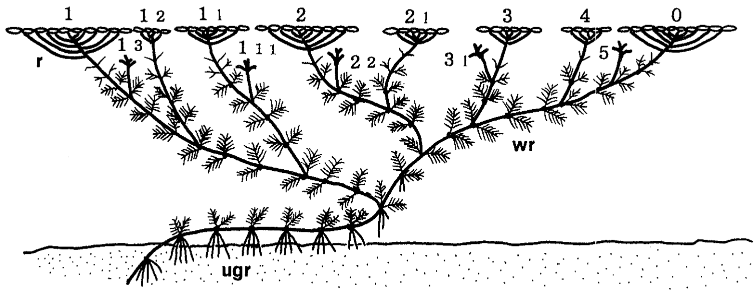

Fig. 3. Schematic drawing of the growth of water chestnut transplanted into a flooded paddy field.
The main stem produces several primary branch stems, and each primary branch stem produces higher order branch stems. One leaf, a pair of water roots and several underground roots emerge at each node to upper node along a stem. Floating leaves develop as a rosette at each stem apex. Some fruits are borne at each stem apex in the reproductive period.
0, main (1st) stem (rosette); 1～5, primary branch (rosette); 1 1～3 1, secondary branch (rosette); 1 1 1, tertiary branch; r, rosette; ugr, underground root; wr, water root.

medium plant growth after releasing ponding water. The fruits were preserved in water and the fresh weight was measured after the exodermis of the fruits was peeled away. The number of productive rosettes per m^2, number of fruits per rosette, and average fruit fresh weight were measured as the yield components. In the present experiment, unripe fruits were also included in the yield to estimate total fruit productivity.

Results

1. Vegetative growth

(1) Leaf emergence and change of rosette number

The seedlings were established about 10 days after transplanting. Then branch stems developed vigorously, and rosettes were formed at each stem apex (Fig. 3). On the stem, one leaf developed per node. Therefore, the number of leaves on the stem was equivalent to the number of nodes formed on the stem. The leaf emergence rate was about 1.5 d^{-1}, and did not vary with the plant until early August, after which it decreased to below 1.0 d^{-1}. The large and medium fruit lines maintained higher leaf emergence rates even after August in comparison with the small fruit lines, and thus, the number of leaves per rosette during the growing season were greater in the former lines than the latter (Table 2).

In every line of water chestnut, as in the case of *Trapa bispinosa* Roxb. reported previously (Arima et al., 1990, 1992a), juvenile floating leaves changed to adult floating leaves in late July, and became emersed leaves by the end of August. The sizes of adult floating leaves and emersed leaves were the largest in large fruit lines followed by medium and small fruit lines in this order (Table 2). The leaf area in each large fruit line was larger than 15 cm^2, which was 2 to 3 times as large as that of the small fruit line. About 30 leaves were formed per rosette of each water chestnut line, so the rosettes of

Table 2. Morphological characters of foliage in water chestnuts.

Line	No. of leaves per rosette 1)	Leaf size 2) (cm^2)	Rosette size 3) Diameter (cm)	Height (cm)
1	104±6.4	17.5±0.8	23±3	7±2
2	109±5.3	17.0±0.7	24±4	7±2
3	110±7.1	17.5±1.3	22±3	6±2
4	103±5.3	19.5±1.6	23±2	7±2
5	100±6.0	21.2±2.1	24±3	10±3
6	99±7.3	11.3±0.7	20±3	5±1
7	75±4.8	15.6±1.2	23±2	8±3
8	71±5.4	7.8±0.4	14±2	3±1
9	85±4.3	6.5±0.8	15±1	3±1
10	78±3.6	7.5±0.4	16±3	3±2
11	73±3.6	5.2±0.5	12±2	3±1
12	84±5.1	6.0±0.3	13±2	3±1

Each value shows Mean±s.d.
1) Measuring period: 5 July～20 Sept.
2) Laminas of adult floating leaves which emerged from 7th, 8th and 9th node on stem were measured using 15 rosettes for each line at 4 Aug.
3) Size of rosettes were measured using 15 rosettes for each line on 4 Sept.

emersed leaves were larger in the large fruit lines (Table 2).

(2) Foliage formation and dry matter production

The number of rosettes per m^2 increased with increasing % covered with floating leaves up to 100%, then decreased to a constant level by self thinning. The number of productive rosettes per m^2 was smaller in the lines with larger rosettes, being about 30 in both the large and medium fruit lines, and about 60 in the small fruit lines (Table 3).

The number of rosettes per m^2, % covered with floating leaves and the start of emersed leaf development were closely related, as reported in previous studies (Arima et al., 1992a, 1992b). In the present experiment, the large fruit lines rapidly increased % covered with

Table 3. Differences in the characteristics of rosettes in water chestnuts.

Line	Date of 100% cover degree with floating leaves	Maximum No. of rosettes (m^{-2})	No. of productive rosettes (m^{-2})	Maximum LAI[1)]
1	31 Jul.	41.3±5.0	33.0±3.4	2.1±0.2
2	2 Aug.	36.2±4.1	32.4±3.0	2.0±0.2
3	7 Aug.	37.5±3.4	30.5±3.3	1.8±0.3
4	10 Aug.	39.5±5.8	32.5±4.5	2.1±0.1
5	5 Aug.	34.6±3.5	29.0±3.5	2.3±0.2
6	11 Aug.	47.3±7.5	36.5±3.0	1.9±0.1
7	11 Aug.	64.5±15.8	32.0±5.0	2.2±0.2
8	13 Aug.	99.5±12.4	49.3±7.5	1.5±0.2
9	13 Aug.	115.7±8.6	63.2±7.5	1.8±0.1
10	18 Aug.	94.5±13.4	52.2±5.1	1.8±0.1
11	12 Aug.	118.2±13.7	67.4±6.8	1.3±0.2
12	20 Aug.	96.5±18.2	60.0±7.2	1.6±0.1

Each value shows Mean±s.d.

1) Maximum LAI of emersed foliage was measured on 4 Sept.

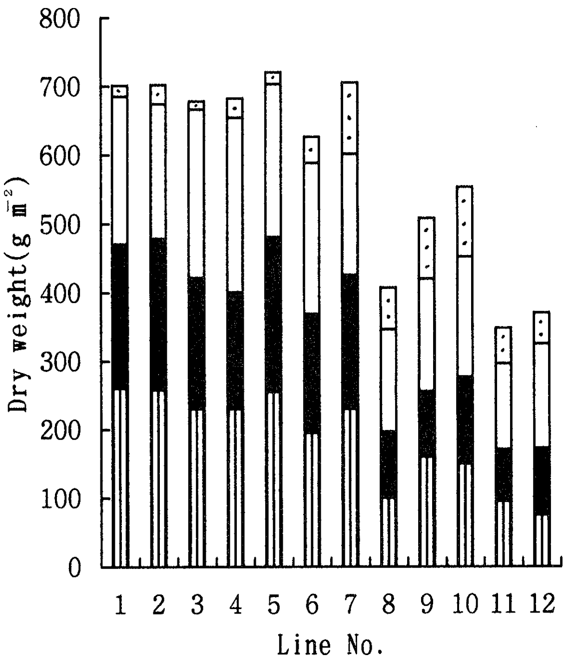

Fig. 4. Dry weight of water chestnut.
▥, leaf; ■, petiol; □, stem; ⊡, fruit.
Dry weight of water chestnut plants excluding roots were measured at 5 Sept. (1-6 lines, mid-ripening period: 7-12 lines, late ripening period).

Table 4. Green level and percentage of water surface covered (% covered) with emersed leaved.

Line	Green level of lamina[1)] 4 Aug.	Green level of lamina[1)] 2 Oct.	% covered with emersed leaves [2)]
1	1.43	1.68	94±8
2	1.36	1.63	90±13
3	1.34	1.62	62±19
4	1.38	1.44	65±18
5	1.30	1.53	89±9
6	1.28	1.20	36±23
7	1.39	1.31	27±20
8	1.42	1.40	4±5
9	1.28	1.23	2±6
10	1.36	1.29	5±10
11	1.41	1.22	0
12	1.45	1.25	4±7

1) Green level was measured with a green meter (CT101, Fujihira Co.). Lamina of 7th, 8th and 9th node from the lamina opening node on stem.

2) Measuring date was 2 Oct.

floating leaves and developed emersed leaves early, whereas the small fruit lines, increased the % covered slowly, and thus the emersed leaves developed 2 to 3 weeks later than the large fruit lines (Table 3). The maximum leaf area index varied from 1.3 to 2.3 among the lines and tended to be larger in the large fruit lines which produced larger dry matter (Table 3).

The dry weights of each organ in the plants with emersed leaf foliage are shown in Fig. 4. The total dry weights, excluding soil roots, were more than 600 g m^{-2} both in the large and medium fruit lines (lines 1～7), and 300 to 500 g m^{-2} in the small fruit lines (lines 8～12). The stems and the leaves were heavier in the large fruit lines than in the small lines. Sometimes, the small fruit lines had heavier fruit than the large fruit lines, because the small fruit lines fruited earlier than the large fruit lines.

After mid-September, newly developed leaves were smaller and did not emerge. Consequently, the emersed leaf foliage gradually changed to the floating leaf foliage and the aged leaves located in the outer parts of the rosette turned red and started to die one after another. At the beginning of October, when the minimum water temperature decreased to below 15°C, the % covered with emersed leaves and green level were measured as the indices of foliage function of each line (Table 4). The % covered with emersed leaves was about 80%, 30% and below 5% for the large, medium and small fruit lines, respectively. At the beginning of August when water chestnut plants were growing vigorously, the green level was high in all lines, but in early October the green level in the medium and small fruit lines decreased suggesting, a reduction of their activities although the level in the large fruit lines was still high.

Table 5. Yield and yield components.

Line	(A) Total fresh weight of fruits(g m^{-2})	(B) Number of productive rosettes(m^{-2})	(C) Number of fruits per rosette	(D) Number of fruits (m^{-2})	(E) Fresh weight of fruit (g)
1	924±78	33.0±3.4	2.5±0.3	82.5±5.0	11.2±0.9
2	978±44	32.4±3.0	2.8±0.2	90.7±2.0	10.8±0.7
3	693±50	30.5±3.3	2.4±0.3	73.2±6.0	9.4±1.2
4	668±59	32.5±4.5	2.5±0.3	81.2±6.4	8.2±0.7
5	568±57	29.0±3.5	2.8±0.4	81.2±4.1	7.0±0.9
6	609±33	36.5±3.0	3.6±0.3	131.3±5.9	4.7±0.5
7	615±28	32.0±5.0	5.3±0.3	169.5±7.5	3.7±0.4
8	417±49	49.3±7.5	7.8±0.7	385.3±38.5	1.1±0.2
9	409±33	63.2±7.5	5.3±0.9	334.4±15.4	1.3±0.2
10	371±17	52.1±5.1	6.1±1.0	317.6±35.2	1.2±0.1
11	325±42	67.4±6.8	5.6±1.0	377.3±32.3	0.9±0.2
12	256±32	60.0±7.2	4.4±0.3	264.0±25.5	1.0±0.1

Yield (A)=(B)×(C)×(E)=(D)×(E). Each value shows Mean±s.d.

2. Yield and yield components

Total fresh weight of fruits per m^2, was 250 to 400 g in the small fruit lines, about 600 g in the medium fruit lines and 550 to 1,000 g in the large fruit lines, and thus, the yield tended to be larger in the lines with larger fruit size (Table 5).

The number of fruits per m^2 was 300 to 400 for the small fruit lines, about 150 for the medium fruit lines, and less than 100 for the large fruit lines; thus, the number of fruits tended to be larger, the smaller the fruit. The number of rosettes per m^2, was around 30 in both the large and medium fruit lines, but about 60 in the small fruit lines. Moreover, the number of fruits per rosette was about 3 in the large fruit lines and 5 to 6 in the medium and small fruit lines, the highest being about 8. Thus, in the small fruit lines, had a larger number of rosettes and larger number of fruits per rosette than large and medium fruit lines. Meanwhile, the average fruit weight was 0.9 to 1.3 g in the small fruit lines, 3.7 to 4.7 g in the medium fruit lines and 7.0 to 11.2 g in the large fruit lines. In short, the large fruit lines had a small number of heavy fruit and the small fruit lines, a large number of light fruit.

Discussion

Water chestnut is a type of aquatic resource plant effectively grown in fresh water areas for food production. However, it is in the stage of acclimatization from wild plant to crop because of the lack of cultivation potential as a crop. For instance, the seed-setting of this plant is scattered, and hand labor is necessary for harvesting. In this study, to obtain the basic data for improving water chestnut into a better food crop, we have cultivated several kinds of water chestnuts distributed in Japan and China and investigated their growth and productivity. Water chestnuts which grow naturally in lakes and marshes in Kyushu germinate in early April, extend numerous branching stems out to the water surface and form foliage of floating leaves. In this experiment, the water chestnuts transplanted to a paddy field in June, were used, and their foliage formation was considered to be somewhat different from those cultivated direct seed sowing. The relationship between cultivation pattern and growth process will be investigated in future researches, and here we discuss only the difference in the function of foliage among the lines under the condition of transplanting culture in a paddy field.

By comparing the leaf emergence rate (increase of node), the leaf size, and the covering speed of the water surface with emersed leaves, we have found that the large fruit lines from China had a foliage-forming capacity superior to those of middle and small fruit lines from Japan. We also found that both the weight and leaf area index of emersed leaves were high in large fruit lines. Considering the fact that photosynthetic rate in emersed leaves is higher than in adult floating leaves (Arima et al., 1988), we supposed that the productivity of the foliage in the large fruit lines increases rapidly and is maintained longer leading to higher productivity than in small fruit lines. However, in this cultivation test, the dry matter production was similar to that of small fruit lines from Japan reported by Tsuchiya (1987) and was a slightly lower than that of large fruit lines reported by Unni (1984). It is not clear whether the cultivation conditions, such as manure level, were suitable for each water chestnut in this experiment.

The time of occurrence of sizing down, turning red and withering of leaves is closely related to the length of maintenance of the productivity of foliage. One of the reasons for early deterioration of foliage may be the peculiar earliness of the species. For example, the earliness of a potato variety is related to the early withering time of leaves. In the late maturing variety, which has a large number of nodes and a large leaf area, the withering of leaves is late and the period of foliage maintenance longer. This leads to a high dry matter production in the late-maturing variety (Nishibe, 1986). In water chestnut also, the earliness related to the growth character of the stem and leaf is considered to be closely related to the differences among lines in foliage life.

The practical fruit yield was 550 to 1000 g m^{-2} in the large fruit lines from China, 600 g m^{-2} in the middle fruit lines from Japan, and 250 to 400 g m^{-2} in the small fruit lines from Japan. From the relationship among yield components, a significant correlation was observed between fruit size and yield. That is, the large fruit lines always had a higher yield than the small fruit lines. In the small fruit lines the fruit number was 4 to 5 fold greater, but total sink capacity was considered to be below half that of the large fruit lines due to the small fruit size.

We have analyzed the correlation between the yield and various characters involved in vegetative growth. The correlation coefficients between yield and each character were as follows ; (1) leaf number per rosette : 0.79, (2) area of individual leaf : 0.78, (3) rosette diameter on 4 Sept. : 0.85 (Table 2), (4) the day for 100% covering (days after transplanting) : 0.90 (Table 3), green level on 2 Oct. : 0.79, and the percentage of remaining emersed leaves : 0.88 (Table 4). All of these correlations were significant at the 1.0% level. Based on the above, the maintenance of leaf activity rather than the early formation and longer durability of large foliage, is considered to be linked with the high material production in large fruit lines. Yield is certainly closely related to environmental conditions as well as the growth characters of the species, such as flowering and seed setting, and we will investigate these relationships in future research.

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