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Overwintering Ability and Dry Matter Production of Sugarcane Hybrids and Relatives in the Kanto Region of Japan

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Abstract

Many kinds of sugarcane hybrids and relatives were planted in two sites, Tsukuba and Nasushiobara, in the northern Kanto region of Japan to evaluate their overwintering ability and biomass production. JW49 (*Saccharum spontaneum* L.), US56-15-2 (*S. spontaneum* L.) and Ponape Hurukimura (*Saccharum barberi* Jeswiet) were able to overwinter in the field experiment conducted in Tsukuba, but not in Nasushiobara. In the field experiment conducted in Nasushiobara, only two lines, JW599 (*Saccharum spontaneum* L.) and JW630 (*Erianthus* spp.), overwintered. JW630 also showed good ratooning ability in Tsukuba, even though the results were obtained from the experiment without replication. The newly planted JW599 and JW630 were small in the first year, but from the second year the biomass production of the ratoon plants became huge. The dry matter yields of JW599 and JW630 in the first year were 0.07 and 0.13 kg per hill, respectively, and the average dry matter yields of JW599 and JW630 during three years of ratoon cultivation were 1.46 and 2.63 kg per hill per year, respectively. Assuming that they are planted at 1.5-m inter-row intervals and 0.3 m inter-hill intervals, and each hill can accumulate the same dry matter yield, the dry matter production of the ratoon plant of JW599 and JW630 is estimated to be 32.5 and 58.4 t/ha, respectively.

Discipline: Crop production
Additional key words: biomass, *Erianthus* spp., *Saccharum spontaneum* L., *Saccharum* spp. hybrid

Introduction

The development of reusable new energy sources is urgently needed to reduce the amount of CO_2 emission. Biomass is a reusable energy source, and sugarcane (*Saccharum* spp. hybrid) is known for its high biomass productivity. Sugarcane can be used as an energy crop in two ways: for bio-ethanol production from sugar, and for utilization as a herbaceous biomass. Brazil uses ethanol from sugarcane juice in its production of fuel, and gasoline containing 25% of ethanol is commonly sold in Bra-

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zil at the moment. There are many ways to use herbaceous biomass, including for cogeneration, methanol conversion, and as pellet fuel. The technology of ethanol production from the cellulose of herbaceous biomass is under development, and it is thought to be promising because it does not require use of the edible part of the biomass crops.

In Japan, the area for cultivating sugarcane for sugar production is mainly in Okinawa and other Nansei Islands in the subtropical region. However, most abandoned agricultural fields suitable for biomass crop production are in the temperate region. If sugarcane had the added abilities to grow well under low temperature conditions and to overwinter, it would be a suitable crop for energy production in the temperate zones of Japan, such as the Kanto region. However, sugarcane grown in temperate zones as a biomass crop would have to be used as a herbaceous biomass rather than in ethanol, because it is thought that accumulating sugar would be more difficult than accumulating fibrous constituents when sugarcane is grown in a temperate region. The fibrous biomass of sugarcane can also be used as an animal feed if it has good feeding value for ruminants.

Interspecific and intergeneric hybrids of sugarcane with *Saccharum spontaneum* L., sorghum, *Miscanthus* spp., and *Erianthus* spp. have been bred at the Sugarcane Experimental Station in Tanegashima, National Agricultural Research Center for Kyushu Okinawa Region (KONARC)[13]. Some of these lines have shown high biomass production derived from high fiber content[18,19], which makes them suitable as biomass crops. Many kinds of sugarcane relatives have different characteristics. For example, lines of *Saccharum sinense* have been planted in Japan's temperate zone for traditional sugar production. *Erianthus* is a wild relative of sugarcane that has desirable traits, including good ratooning performance and tolerance to environmental stresses[4]. Nagatomi and Degi collected wild sugarcane species from the Nansei Islands and the mainland of Japan[15]. More than 700 accessions were designated as the JW (Japan Wild) series including *S. sinense* Roxb., sugarcane wild species (*Saccharum spontaneum* L.) and wild relatives (*Miscanthus* spp. and *Erianthus* spp.), and mainland wild species showed remarkable tolerance to cold weather.

Research on crops for herbaceous biomass production was carried out in the United States and Europe[9], and miscanthus (*Miscanthus* spp.), giant reed (*Arundo donax*), and switchgrass (*Panicum virgatum*) were selected as promising candidates, because they are able to produce high biomass in the temperate zone and perennial grasses. The perennial rhizomatous grasses can reduce the cost of plowing, sowing seeds, and basal dressing. Herbaceous biomass production of feed crops was studied in the Kanto region of Japan, and the dry matter yields of sorghum (*Sorghum bicolor*) cv. Ultrasorgo as a summer crop and rye (*Secale cereale* L.) cv. Haruichiban as a winter crop were 23.1 t/ha and 9.9 t/ha, respectively[10]. The total dry matter yield per year was comparable to that of perennial grasses, but the selection of suitable perennial grasses is expected to reduce production costs. Ratoon plant cultivation is common in sugarcane cultivation. Ratoon is the production of a new crop from the regrowth of new shoots after harvest cutting without replanting[23]. Therefore, sugarcane lines that can overwinter and produce many ratoons may be suitable crops for herbaceous biomass production in the temperate zone.

In order to identify other promising biomass lines, two field experiments were conducted in Tsukuba and Nasushiobara cities in the Kanto region to evaluate the overwintering ability and dry matter production of many kinds of sugarcane hybrids and relatives. In addition, nutrient accumulations in a plant were analyzed to obtain basic information on fertilizer application.

Materials and methods

1. Field experiment in Tsukuba (Exp. 1)

A total of 27 kinds of nursery plants, including cultivated sugarcane varieties (*Saccharum* spp. hybrid, *S. sinense* Roxb, and *S. barberi* Jeswiet), interspecific and intergeneric hybrids of sugarcane, and wild relatives of sugarcane (*Saccharum spontaneum* L. and *Erianthus* spp.) were prepared (Table 1). It should be noted that with these interspecific and intergeneric hybrid lines, the possibility of self-pollination could not be excluded, except for KRSp93–19, which was evaluated with molecular markers (Terajima et al., 2007, unpublished data).

The stems of the sugarcane varieties, hybrid lines, and wild relatives were cut into 7-cm pieces with one node and axillary bud, and then raised for about two months in a greenhouse. Five nurseries of each plant were transplanted with two replicates on May 15, 2002, to an upland field of the Japan International Research Center for Agricultural Sciences in Tsukuba (36°03'N, 140°05'E), located in the northern Kanto region of Japan. The soil type was Andosol (volcanic ash soil). The inter-row and hill intervals were 1.8 and 0.5 m, respectively. Chemical fertilizer was applied beside the hills on June 13 and August 12. The amount of fertilizer used for the first and second application was $N:P_2O_5:K_2O=6:6:6$ (g/m^2) and $N:P_2O_5:K_2O=9:9:9$ (g/m^2), respectively. The aboveground part was harvested on November 4. The stubble was then cut just above the ground on December 17, and covered by about 3 cm of soil during winter.

In order to evaluate overwintering ability, we continued to grow ratoon plants in 2003, and the dates when ratoon stubble sprouted were recorded and the number of ratoon stubble was counted.

2. Field experiment in Nasushiobara (Exp. 2)

A total of 24 kinds of nursery plants, including cultivated sugarcane varieties (*Saccharum* spp. hybrid, *S. sinense* Roxb, and *S. barberi* Jeswiet), interspecific and intergeneric hybrids of sugarcane, wild relatives of sugarcane (*Saccharum spontaneum* L. and *Erianthus* spp.), and napiergrass (*Pennisetum purpureum* Schumach) were prepared (Table 1). Napiergrass was planted as a reference crop of dry matter production, because it is known that the dry matter yields of napiergrass and sugarcane in a subtropical climate greatly exceed the yields of other C_4 species[24].

Four nurseries of each plant were transplanted with

Table 1. Varieties/Lines provided for field experiments

Varieties/Lines	Note	JP No.	Exp. 1	Exp. 2
NCo310	Sugarcane (*Saccharum* spp. hybrid)	171861	○	○
Ni6	Sugarcane (*Saccharum* spp. hybrid)	152781	–	○
NiF8	Sugarcane (*Saccharum* spp. hybrid)	172051	○	○
Chikucha	*Saccharum sinense* Roxb.		–	○
Natal Uba	*Saccharum sinense* Roxb.	172123	–	○
Yomitanzan	*Saccharum sinense* Roxb.	171899	○	○
Chunnee	*Saccharum barberi* Jeswiet	172061	○	○
Ponape Hurukimura	*Saccharum barberi* Jeswiet	172023	○	○
97S-27	SIH (G30, SGF1 x US56-15-2, SS)		○	○
97S-33	SIH (G30, SGF1 x US56-15-2, SS)		○†	○
97S-49	SIH (G38, SGF1 x US56-15-2, SS)		○	–
97S-51	SIH (G38, SGF1 x US56-15-2, SS)		○	○
KRSp93-19	SIH (NCo310, SCV x Glagah Kloet, SS)		○	○
KRSp93-25	SIH (Ni6, SCV x Glagah Kloet, SS)		○	–
KRSp93-30	SIH (Ni6, SCV x Glagah Kloet, SS)		○	○
S3-27	SIH (IRK67-1, SCV x Glagah Kloet, SS)		○	○
S5-14	SIH (NCo310, SCV x Glagah Kloet, SS)		○	–
S5-16	SIH (NCo310, SCV x Glagah Kloet, SS)		○†	○
97GA-4	SIH (G38, SGF1 x G75, SGF1)		○	–
97GA-18	SIH (Ni6, SCV x RibbonCane, SGV)		○	○
97GA-36	SIH (Ni9, SCV x AmberBlack, SGV)		○	–
97GS-95	SIH (Ni9, SCV x AmberBlack, SGV)		○	–
95GA-18	SIH (SK-13, SGF1 x Sumac, SGV)		○	–
97S-100	SIH (F146, SCV x IJ76-349, E)		○	○
97S-107	SIH (F146, SCV x IJ76-349, E)		○	–
US56-15-2	*Saccharum spontaneum* L., WSC	172082	○	○
JW49	*Saccharum spontaneum* L., WSC	174470	○	○
JW385	*Saccharum spontaneum* L., WSC		○†	○
JW599	*Saccharum spontaneum* L., WSC	173948	–	○
IK76-126	*Erianthus* spp.		○†	○
JW630	*Erianthus* spp.	173957	○†	○
Merkeron	Napiergrass (*Pennisetum purpureum* Schumach)		–	○

JP No.: accession number of the National Institute of Agrobiological Sciences (NIAS) Genebank, SIH: sugarcane interspecific or intergeneric hybrids, SGF1: F1 between sugarcane and sorghum, SS: *Saccharum spontaneum* L., SCV: sugarcane (*Saccharum* spp. hybrid) variety, SGV: sorghum (*Sorghum bicolor*) variety, E: *Erianthus* spp. WSC: wild species of sugarcane, (female parent x male parent), †without replication.

two replicates on June 18, 2003, to the upland field of the National Institute of Livestock and Grassland Science in Nasushiobara (36˚55'N, 139˚56'E), located in the northern Kanto region of Japan. The soil type was Brown Lowland soil. The inter-row and hill intervals were 1.5 and 0.3 m, respectively. Chemical fertilizer was applied beside the hills at planting on August 11 and September 10. The amount of fertilizer used at the first, second, and third application was $N:P_2O_5:K_2O=6:6:6$ (g/m^2), $N:P_2O_5:K_2O=9:9:9$ (g/m^2), and $N:P_2O_5:K_2O=6:6:6$ (g/m^2), respectively. The stems were cut at about 10 cm above the ground at harvest on November 27, and the stubble was not covered by soil. The ratoon plants continued to grow in 2004, 2005, and 2006. Fertilizer was applied on June 25, August 13, and September 13 of 2004, May 19, July 28, and September 2 of 2005, and April 28, July 28, and August 24 of 2006. The amount of fertilizer was $N:P_2O_5:K_2O=6:6:6$ (g/m^2) per application. The harvest dates were November 9, 2004, October 19, 2005, and October 26, 2006.

At harvest, the aboveground part was sampled and the fresh weight of the whole samples and sub samples were weighed in the field. In order to determine the dry matter weight, the sub samples were weighed again after being dried in an oven at 70ºC for a few days until the weight stopped decreasing. In 2005 and 2006, the plants' nutrient accumulation was measured. Dried plant samples were ground into a fine powder using a mill and digested with sulfuric acid and hydrogen peroxide. The nitrogen, phosphorus, and potassium concentration in each plant sample was measured by the Kjeldahl distillation method, emission spectrography with vanadomolybdate, and the atomic absorption analysis method, respectively.

The results were analyzed using the Ekuseru-Toukei 2008 (Social Survey Research Information Co., Ltd., Tokyo) statistical program. Analysis of variance was performed. The results were considered statistically significant at the 5% probability level.

Results

1. Meteorological feature

Meteorological data for Tsukuba were provided by the Japan Meteorological Agency. The meteorological data for Nasushiobara were provided by the National Institute of Livestock and Grassland Science. The monthly mean air temperature, monthly mean maximum air temperature, monthly mean minimum air temperature, and monthly total precipitation of both places are shown in Fig. 1.

In Tsukuba in 2002, the monthly mean air temperatures from June to September were over 19ºC and those of May and October were around 17ºC. The total rainfall during the growing season was 637 mm. In Nasushiobara, the monthly mean air temperatures from June to September were over 19ºC and those of May and October were around 15ºC. The total rainfall during the growing season, from planting (in 2003) or May to harvest, was 907 mm, 1408 mm, 1222 mm, and 1316 mm in 2003, 2004, 2005, and 2006, respectively.

The temperature conditions that influence overwintering ability are low temperatures and periods of exposure to low temperature. January was the coldest month in both places. In January 2003, the monthly mean air temperature and monthly mean minimum air temperature in Tsukuba were 2.5ºC and -3.0ºC, respectively. In January 2004 in Nasushiobara, these temperatures were 0.7ºC and -3.9ºC, respectively. In Tsukuba, the monthly mean minimum air temperatures in December, January, and February dropped below freezing. In Nasushiobara, the monthly mean minimum air temperatures over the four months from December to March were below zero, as they were in the following two years.

2. Overwintering ability evaluated by the field experiment in Tsukuba

The overwintering ability in the field experiment in Tsukuba differed significantly depending on the varieties and lines (Table 2). Among the 27 kinds of plants, 16 varieties and lines showed new germination from stubble in the spring of 2003. Three lines of wild relatives of sugarcane, *Saccharum spontaneum* lines JW49 and JW385 and *Erianthus* spp. line JW630, showed ratoon sprouting from all the stubble, followed by *Saccharum spontaneum* line US56–15–2 and *Saccharum barberi* line Ponape Hurukimura with a high survival rate of 90%, which was the ratio of the number of ratoon stubble per total number of stubble. Three hybrid lines between sugarcane and *S. spontaneum*, KRSp93–30, S5–14, and S3–27, were also in the third highest group with a 30 to 50% survival rate. The date of sprouting of JW630, when half or more than half of the ratoon stubble sprouted, was the earliest (April 11), and those of three lines, NiF8, KRSp93–19, and 97S–100, were the latest (May 30 and June 3). Those of the other 12 lines were between April 24 and May 9. The survival rate did not correlate with the date of sprouting.

3. Overwintering ability, dry matter yield, and nutrient accumulation evaluated by the field experiment in Nasushiobara

The dry matter yields of Exp. 2 differed significantly among varieties/lines ($P < 0.001$). Napiergrass grew well, while there were small yields of the sugarcane cultivated varieties, hybrid lines, and wild relatives of sugarcane in the field experiment in Nasushiobara in 2003 (Table 3). Only JW599 (*S. spontaneum*) and JW630 (*Erianthus* spp.) showed overwintering ability, and the ratoon plants of these lines continued to grow in 2004. The survival rate of JW599 and JW630 was 88 and 100%, respectively. The other lines, including napiergrass, sugarcane cultivated varieties, hybrids, and relatives, could not survive the winter in Nasushiobara.

The dry matter yields of JW599 and JW630 in the first year were 0.07 and 0.13 kg per hill, respectively, and those in 2004 increased more than 10 times (Table 4). All stubble of JW599 and JW630 overwintered again and the ratoon plants continued to grow in 2005 and 2006. The dry matter yields of these lines increased in 2005 and decreased in 2006. The dry matter yields of JW630 were significantly greater than those of JW599 ($P < 0.001$). The maximum dry matter yields of JW599 and JW630 were 2.11 and 3.86 kg per hill in 2005, respectively. The four-year averages of the percentage dry matter of JW599 and JW630 were 35.8% and 38.6%, respectively. Those values were higher than the 16.6% of napiergrass cv. Merkeron in 2003.

The nitrogen, phosphorus, and potassium concentrations and the total amount of these nutrient accumulations in the aboveground part of one plant of JW599 and JW630 in 2005 and 2006 are shown in Table 5. No significant difference was found in the concentrations of nitrogen, phosphorus, and potassium, but the total accumulations of nitrogen, phosphorus, and potassium were significantly different between the two years and between the two lines. The amount of nutrient accumulation by JW630 in 2005 was the largest at 35.5 g of nitrogen, 5.8 g of phosphorus, and 23.3 g of potassium.

Discussion

Ratooning of sugarcane requires the survival and germination of an underground bud on a subterranean stem. Therefore, the characteristics of the subterranean stem and environmental conditions under the ground are

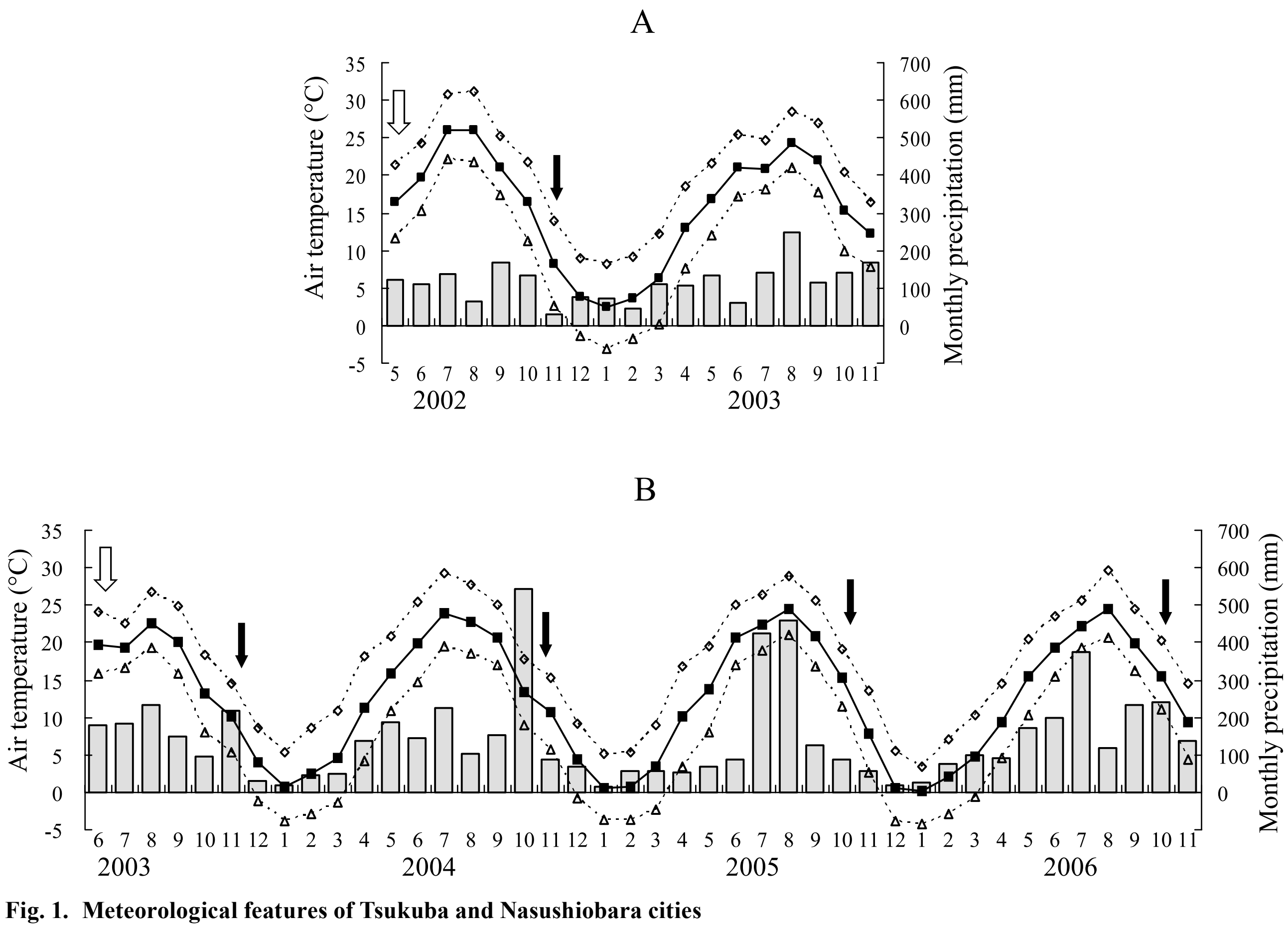

Fig. 1. Meteorological features of Tsukuba and Nasushiobara cities
A: Tsukuba from 2002 to 2003, B: Nasushiobara from 2003 to 2006.
◊: monthly mean maximum air temperature, ■: monthly mean air temperature, Δ: monthly mean minimum air temperature, gray bar: monthly precipitation, white arrow: transplanting, black arrow: harvest.

important[25]. Takamura et al. cultivated commercial sugarcane in the temperate zone and reported that only stubble that was covered by plastic sheets was able to overwinter, when the average minimum air temperature of 10 days was below zero[20]. In Tsukuba and Nasushiobara, the average minimum air temperature was below zero for three and four months, respectively, meaning the cold period was too long for ratooning of commercial sugarcane. However, several varieties and lines showed overwintering ability in Tsukuba, and two wild relatives, JW599 and JW630, survived in Nasushiobara. The origins of JW49, JW599, and JW630 are Okinawa, Chiba, and Shizuoka prefectures in Japan, respectively. JW599 and JW630 were collected north of their distribution in the temperate zone of Japan. Miller evaluated the cold tolerance of sugarcane and reported that there were resistant lines in the wild relatives of sugarcane[14]. It is possible that the buds of JW599 and JW630 may have freezing resistance. In the field experiment conducted in Tsukuba, the *Saccharum sinense* line Yomitanzan did not survive, even though lines of *Saccharum sinense* are known to grow in the temperate zone of Japan and have been used to make traditional Japanese-style confectionary in Kagawa and Tokushima prefectures.

JW49, US56–15–2, and Ponape Hurukimura could overwinter in Tsukuba, but they did not survive in Nasushiobara. A lower monthly mean air temperature and a lower monthly mean minimum air temperature in January 2004 in Nasushiobara than in January 2003 in Tsukuba is considered one of the reasons (Fig. 1). Covering the stubble with soil after harvest in Tsukuba might help the plants survive, too. In Tanegashima, which is the northern limit of sugarcane cultivation for sugar production in Japan, mulching by biodegradable plastic sheets is a common practice and increases the yield of ratoon plants by enhancing good sprouts and increasing the stalk number[17]. However, it has been shown that a greater yield was obtained from some varieties without mulching than from NiF8, which is a leading variety in Tanegashima, with mulching[21]. Therefore, selecting a suitable variety/line should be considered first in order to establish low-cost biomass production in the temperate zone.

In the field experiment conducted in Nasushiobara, the biomass production of newly planted JW599 and JW630 was low in the first year, but in the second year, the biomass production of ratoon plants became very large (Table 4). The yield of ratoon crops showed a general decline year after year until the manager decided that it was time to replant[7]. A short growing period in the first year was one reason why there was low dry matter production of the aboveground part of the plants in the first year. The root system, however, might develop well during this period. Fukuzawa et al. also reported that the dry matter yield at the initial stage of *Erianthus* spp. line IK 76–126 was smaller than that of sugarcane varieties, but the top-root ratio of the dry matter of *Erianthus* was lower than that of sugarcane varieties[6]. At ratoon cultivation, new stems of JW630 germinated from the circumference of the stubble and did not germinate from the center of the stubble. The hills, which were next to each other, were contacted in 2005, because the inter-hill interval (0.3 m) was too narrow, and new stems could not sprout from between two hills. This may be one of the reasons why the dry matter yield of JW630 in 2006 decreased. In contrast, the new stems of JW599 were randomly distributed. The average dry matter yields of JW599 and JW630 during the three-year ratoon cultivation from 2004 to 2006 were 1.46 and 2.63 kg per hill per year, respectively. Assuming that they are planted at 1.5-m inter-row intervals and 0.3-m inter-hill intervals, and each hill can accumulate the same dry matter yield, the dry matter production of the ratoon plant of JW599 and JW630 is estimated to be 32.5 and 58.4 t/ha, respectively.

Sugarcane and napiergrass are C_4 plants and have high biomass productivity. They are commonly grown in tropical or subtropical regions. The dry matter accumu-

Table 2. Survival rate and sprouting date of ratoon stubble of the Exp. 1 in 2003

Varieties/Lines	Survival rate (%)	Date of sprouting
JW49	100	Apr. 28
JW385†	100	Apr. 28
JW630†	100	Apr. 11
US56-15-2	90	May 9
Ponape Hurukimura	90	May 9
KRSp93-30	50	May 4
S5-14	40	May 1
S3-27	30	May 9
97GS-95	20	Apr. 28
NiF8	10	May 30
97S-51	10	May 1
KRSp93-19	10	June 3
97GA-36	10	Apr. 24
95GA-18	10	Apr. 24
97S-100	10	May 30
97S-107	10	Apr. 28

Varieties/Lines which did not ratoon are not shown in the table. Survival rate (%): average of rate of ratoon stubble per total stubble, Date of sprouting: date when half or more than half of the ratoon stubble sprouted, †without replication.

lation of sugarcane and napiergrass were reported to be 49.0 and 47.0 t/ha in a subtropical climate in Florida[24]. When sugarcane and napiergrass were grown in field experiments in temperate zones, the maximum dry matter yields of sugarcane and napiergrass were 38.4 t/ha in Wakayama, Japan[20], and 52.8 t/ha in Fukuoka, Japan[8], respectively. The dry matter yields of the hybrid line KRSp93–30 in Tanegashima were 30.2 t/ha and 58.5 t/ha for

Table 3. Dry matter yield of the Exp. 2 in 2003

Varieties/Lines	Dry matter yield (g/hill)		
	Rep. 1	Rep. 2	Average
Merkeron	785	1124	955 a
S5-16	666	634	650 ab
US56-15-2	617	616	617 abc
97S-51	417	683	550 abcd
KRSp93-19	427	620	524 abcd
KRSp93-30	387	534	461 abcd
97S-33	264	638	451 abcd
S3-27	436	455	446 abcd
97S-27	145	726	436 bcd
IK76-126	266	349	308 bcd
97GA-18	343	243	293 bcd
JW49	280	303	292 bcd
Ponape Hurukimura	240	261	251 bcd
Yomitanzan	210	252	231 bcd
NCo310	185	245	215 bcd
Chikucha	199	200	200 bcd
Natal Uba	191	197	194 bcd
Chunnee	180	146	163 bcd
97S-100	121	199	160 bcd
Ni6	194	85	140 bcd
NiF8	133	146	140 bcd
JW630	158	105	132 cd
JW385	84	164	124 cd
JW599	62	72	67 d
P value	Varieties/Lines		<0.001

Values followed by the same letters are not significantly different ($P<0.05$).

Table 4. Dry matter yield (g/hill) of the Exp. 2 from 2003 to 2006

Variety/Lines		2003	2004	2005	2006	Average of ratoon plants
Merkeron		955				
JW599		67 c	949 b	2110 a	1326 b	1461
JW630		132 d	1441 c	3863 a	2578 b	2627
P value	Year			< 0.001		
	Lines			< 0.001		
	Year x Lines			< 0.001		

Average of two replications. Statistic analysis is performed except for the dry matter yield of Merkeron in 2003. Values followed by the same letters within the same line are not significantly different ($P<0.05$). Average of ratoon plants means average of dry matter yield (g per hill per year) in 2004, 2005 and 2006.

the plant and the ratoon crop, respectively[19]. Recently, the first sugarcane variety for animal feed, KRFo93–1, was released by KONARC. It was harvested three times in two years and the total dry matter yield was 50 t/ha per year[16]. Sugarcane hybrid lines were planted in an upland field in Tsukuba and the average dry matter yields of three planting crops of 97S–51, KESp93–19, and 97S–107 were 37.5 t/ha, 35.9 t/ha, and 37.2 t/ha, respectively. Furthermore, the dry matter yield of sorghum cv. Tentaka was 44.9 t/ha in the same experiment[26]. According to a review on perennial rhizomatous grasses as energy crops in the United States and Europe[10], the maximum dry matter yields of miscanthus, giant reed, and switchgrass were 44 t/ha in Greece, 37 t/ha in Spain, and 34.6 t/ha in Alabama, respectively.

The estimated dry matter production of JW599 and JW630 was comparable to these records of maximum dry matter yield, and these two lines are considered to be promising new energy crop candidates. It is reported that the cold tolerance of wild sugarcane relatives could be introduced to the commercial sugarcane varieties by crossing[5]. By using JW599 and JW630 as a breeding material to transfer overwintering ability, the cultivation area of sugarcane for energy production could be extended. Sugarcane requires an average air temperature of at least 15ºC for minimum growth and 20ºC for normal growth[20]. In Nasushiobara, the total rainfall during the growing season, from planting (in 2003) or May to harvest, was 907 mm, 1408 mm, 1222 mm, and 1316 mm in 2003, 2004, 2005, and 2006, respectively, and it is thought that the amount of precipitation is enough for sugarcane cultivation. The monthly mean air temperatures from June to September were over 19ºC but those of May and October were around 15ºC. Even though there is a sufficient amount of precipitation, only about four months are suitable for growing sugarcane in Nasushiobara. However, a significant amount of dry matter could be obtained from JW599 and JW630, and they may therefore have the ability to grow in lower temperatures than sugarcane and/or grow more rapidly than sugarcane in a short period.

In 2005, JW630 accumulated 35.5 g of nitrogen, 5.8 g of phosphorus, and 23.3 g of potassium per hill (Table 5). These amounts were larger than those supplied by chemical fertilizer of 8.1, 3.5, and 6.7 g per hill per year, respectively. It was reported that *Erianthus* spp. in Thailand had a deep and well-developed root system[12]. We also observed that JW630 had a deep and well-developed root system (data not shown). Therefore, it is possible that the developed root system of JW630 was able to obtain more nutrients from soil. However, the absorption of more nutrients than can be supplied by applied fertilizer may eventually lead to deterioration of the soil. The other possibility for acquiring nitrogen might be endophytic nitrogen fixation, which was reported for sugarcane[2,3]. Using the ^{15}N dilution technique in pots and in concrete tanks, some Brazilian sugarcane varieties showed up to a 70% and 40 to 60% contribution of biological nitrogen fixation to total plant nitrogen, respectively[11,22]. It was also estimated to be about 30% in the sugarcane varieties of Thailand[1]. Further studies to elucidate more details on plant nutrition are needed for the sustainable production of *Erianthus* spp. Field experiments in a larger area are also needed to more accurately determine the yields of JW599 and JW630. Further field trials to find the optimal planting density and fertilizer dose should also be conducted.

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Table 5. Nutrient concentration and total amount of nutrient accumulation of aboveground part of the Exp. 2 in 2005 and 2006

Lines	Year	Concentration (%)			Total accumulation (g/hill)		
		N	P	K	N	P	K
JW599	2005	0.77	0.15	0.78	15.3	3.0	15.4
	2006	0.66	0.17	0.54	8.4	2.1	6.9
JW630	2005	0.98	0.16	0.65	35.5	5.8	23.3
	2006	0.81	0.16	0.68	20.1	3.8	16.9
P value	Year	= 0.162	= 0.784	= 0.230	= 0.003	= 0.034	= 0.016
	Lines	= 0.093	= 0.965	= 0.922	< 0.001	= 0.007	= 0.009
	Year x Lines	= 0.747	= 0.628	= 0.184	= 0.063	= 0.281	= 0.606

Average of two replications.

Council, Japan.

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