Agronomic Factors Affecting the Potential of Sorghum as a Feedstock for Bioethanol Production in the Kanto Region, Japan

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Abstract: In the Kanto region in Japan, the possibilities of running a bio-ethanol plant from rice straw has been assessed and sorghum production has been considered as a necessary part of the system. Two field experiments were conducted in 2012 and 2013 at the NARO—Agricultural Research Center in Tsukuba, Ibaraki to estimate yielding ability of sorghum in the Kanto region. Two cultivars of sweet sorghum and one of grain sorghum were sown using a pneumatic seeder. Above-ground dry matter (DM) yield ranged from 1.03 to 1.82 kg m^{-2} for the sorgo type cultivars and from 0.70 to 1.18 kg m^{-2} for the grain type cultivar. The observed yields were lower than the simulated potential yields, i.e., 1.61 to 2.66 kg m^{-2}, indicating that biomass production was restricted in this study. Stem brix values for the sweet sorghum cultivars were generally low (3.3–16.2%) compared with the values reported in the literature. It appears that there is still room to improve the field management of sorghum to minimize the gap between the potential and actual production observed in these experiments.

Keywords: bioethanol; feedstock; the Kanto region; potential yield; sweet sorghum

1. Introduction

Unlike the southwest islands where sugarcane is almost exclusively expected to play a key role as a feedstock for bio-ethanol plants [1], rice straw is likely to be a major feedstock in the Kanto region [2,3]. Effective utilization of lignocellulosic biomass has been attempted by many researchers at both laboratory [4,5] and plant scales [6]. Issues of cost relative to those of fossil fuel are probably the major challenge to commercial implementation, i.e., construction and management of an actual plant. Cost aside, handling of by-products would arise as another major issue to be solved. Supposing an ethanol plant that has the capacity to produce 15,000 kL of ethanol annually, a similar capacity to a plant that used to work in Hokkaido (Hokkaido bioethanol, Co., Ltd.), 150,000–300,000 kL of vinasse could be generated, assuming the ratio of 10–20 to the ethanol [7]. Being stripped of energy in the form of ethanol, vinasse still contains organic matter and therefore has a high chemical oxidative demand (COD). Releasing it casually, for example, into surface waters would not only be damaging to the environment but also be regarded as a waste of valuable energy and nutrients. In Brazil, the practice of applying sugarcane vinasse to fields to replace mineral fertilizers has been accused of causing

environmental problems including odor and possible emissions of greenhouse gasses where anaerobic digestion is suggested as a possible remedy [8]. An ethanol plant in the Kanto region with the major feedstocks being rice straw, vinasse could be applied to paddies but only at a particular time of year when rice needs nutrients for growth, while vinasse is generated in the ethanol plants all year round or close to it. It would therefore be necessary to develop cropping systems, apart from paddies, that could receive vinasse at various timings throughout the year. It would be preferable if the constituent crops could contribute to the operation of the ethanol plant as feedstocks when necessary. It would also be beneficial to incorporate double purpose cropping like the one reported on wheat [9] which employs a chance-seeking way of production, i.e., growers can change the usage of the standing crop in the field according to the prevailing meteorological and socioeconomic conditions, within a newly developed cropping system. It is known that sugarcane mills in Brazil have been altering the ratio of production of ethanol to sugar according to the demand [10], this flexibility within the biofuel industry is clearly advantageous where competition for fertile cropland for food production is concerned [11].

Sorghum has long been used as staple, sugar and feed crop in arid and semi-arid areas prone to drought [12,13], although its use especially for sugar [14] and as feed [15] has spread to temperate regions. Sorghum has been widely recognized as a potential source of biofuel since the era of oil shock in the 1970s [16–18] due to its ability to produce high biomass and sugars from a relatively short growing period. The recent upsurge in the number of biomass studies could largely be attributable to the adoption of the Kyoto protocol in 1997 [19], which was concerned in part with the increasing greenhouse gas emissions caused by anthropological activities. Recent field studies conducted at relatively high latitudes have generally focused on the characterization of sorghum as a feedstock and on estimating the amount of producible ethanol [20–22]. In addition, some studies have looked at the effects of planting date and/or harvest date on sorghum biomass yield in the context of energy production [23–26].

In Japan, reflecting an increased demand by growers to use sorghum as a feed crop after the 1950s [27], a substantial number of studies can be found in the literature on this crop [28,29]. However, the number of domestic studies clearly placing sorghum as a feedstock for biomass-energy industry is rather limited. Hoshikawa [16,17] was probably among the first to have recognized the potential for sorghum to be a biomass crop in the country. He and his group have conducted extensive work particularly focusing on sweet sorghum, the type that accumulates sugar in stem, in the Tohoku region [17,18,30,31]. Wu et al. [32] has reported above-ground DM yield of a grain sorghum variety (12.85 Mg ha^{-1}) and of two sweet sorghum varieties (22.75 Mg ha^{-1} and 23.66 Mg ha^{-1}) planted in Minamiminowa located in the Chubu region. In the Kanto region, Yasui et al. [33,34], in a series of studies conducted under the project named "biomass transmutation plan" funded by MAFF, investigated stem constituents, especially sugars of sorghum sown on different planting dates. However, they did not investigate the biomass yielding ability of sorghum. Inuyama et al. [27] obtained stem fresh weights in the range of 33.7–44.8 Mg ha^{-1} for three sorghum cultivars planted on 20 May. The DM yield, however, was unfortunately not clear from their study.

The objective of the present study was to estimate the potential biomass yield of sorghum in upland cropping systems in the Kanto region for different planting dates with the aid of simple simulation techniques. Estimation of potential biomass yield was used to help identify the factors that could possibly hinder successful sorghum production in the target region as well as proposing necessary production techniques to overcome these factors. Establishing and running a biomass energy system requires cooperation among stakeholders of different interests and disciplines. It is hoped that the present study will provide an agronomic perspective on this issue so that participants and stakeholders of present and future biomass energy projects can have information about feedstock crops (e.g., sorghum) in terms of climate and crop management systems.

2. Materials and Methods

2.1. Field Experiments

A field experiment was conducted in a field at the NARO—Agricultural Research Center (the predecessor of the Central Region Agricultural Research Center, NARO) ($36°02'$ N, $140°10'$ E) (3–1–1, Kannondai, Tsukuba, Ibaraki, 305-8666, Japan) in 2012 and 2013. pH (H_2O), total nitrogen, available phosphoric acid, exchangeable potassium and humus content in the soil sampled in 2013 were 6.5, 0.35%, 1.5 mg/100 g, 65.3 mg/100 g and 6.8%, respectively. Seeds of three sorghum cultivars, SIL05 (NARO), high sugar sorgo (FS501) (Snow brand seed, Sapporo) and meter sorgo (8080) (TAKII & Co., Ltd., Kyoto, Japan) were sown using a pneumatic seeder (AS404-HW, KUBOTA). SIL05 and FS501 are sweet sorghum, while 8080 grain sorghum. Sowing dates and seed rates are presented in Table 1. The target seed rates were 20, 10, and 10 for SIL05, FS501 and 8080, respectively, depending on the size of the seeds of each cultivar. Furrow spacing was 0.7 m. Nitrogen, phosphorus and potassium of a high analysis compound fertilizer (N, P_2O_5, K_2O; 14%, 14%, 14%) were set to be applied as side dressing at sowing at the rate of 12 g m^{-2} (Table 2). A split-plot design with two replicates was applied with the main plot being sowing date. The size of each plot was 5.6 m by 48 m. After harvesting and the removal of the above-ground parts of the sorghum crop, the field was planted with winter crops mostly oat in 2012 and rye in 2013.

Table 1. Seed rates over two seasons.

| Cultivar | Seed Rate (m^{-2}) | | | | |
| | 2012 | | | 2013 | |
	17 May	7 June	26 June	13 May	28 May
SIL05	21.7	26.5	34.2	32.4	32.5
FS501	10.7	10.8	15.9	16.1	14.8
8080	11.4	10.7	16.5	16.5	13.3

Table 2. Fertilization rates (g m^{-2}) applied over two seasons.

Year	Sowing Date	N	P_2O_5	K_2O
2012	17 May	12.2	12.2	12.2
	7 June	11.6	11.6	11.6
	26 June	9.3	9.3	9.3
2013	13 May	10.7	10.7	10.7
	28 May	10.6	10.6	10.6

2.2. Sampling and Analysis

Above-ground biomass of known area, i.e., 1.4 m^2 (two rows), was harvested every two weeks until harvest (Table 3). In 2013, samples, except for harvest, were taken from an area of 0.7 m^2 (a single row) instead of two rows, as it was found difficult to take hold of two rows of plants showing average growth, i.e., plants of either row tended to show a poor growth. For the sampled plants, height was measured and effective tiller number counted. A part of each sample consisting of 2–3 plants (sub-sample A) was taken, separated to each organ, i.e., leaf blade, stem and leaf sheath and then its fresh weight was determined. Sub-sample A was dried at 80 °C in an oven to constant weight and DM weight was then determined. Another part of each sample, the size of which was similar to that of sub-sample A (sub-sample B) was taken to determine leaf area index (LAI) using an automatic area meter, AAM-8 (Hayashi Denko co Ltd., Tokyo, Japan). At the same time, weeds were also sampled from the same area where sorghum plants were sampled and then their DM weight determined by the same method used for the sorghum samples. After heading, the brix value of stems was measured using a ref brix, PR-101α (ATAGO, Tokyo, Japan).

Table 3. Sampling dates and days after sowing (DAS) over two cropping seasons.

Year	2012						2013			
Sowing (Date)	Early (17 May)		Medium (7 June)		Late (26 June)		Early (13 May)		Medium (28 May)	
Sampling	Date	DAS	Date	DAS	Date	DAS	Date	DAS	Date	DAS
1st	12 June	26	3 July	26	26 July	30	18 June	36	25 June	28
2nd	26 June	40	17 July	40	8 August	43	2 July	50	9 July	42
3rd	10 July	54	31 July	54	22 August	57	16 July	64	22 July	55
4th	24 July	68	14 August	68	5 September	71	30 July	78	6 August	70
5th	7 August	82	28 August	82	19 September	85	13 August	92	20 August	84
6th	21 August	96	11 September	96	3 October *	99	26 August	105	3 September	98
7th	4 September	110	25 September *	110			9 September *	119	17 September *	112
8th	12 September *	118								

* Last sampling is referred to harvest.

2.3. Statistical Analysis and Simulation

Analysis of variance (ANOVA) and the following multiple comparisons by Bonferroni's test as well as regression analysis were performed using an SPSS 13.0 (IBM Japan, Ltd., Tokyo, Japan). Intercepted radiation was calculated on a daily basis from emergence to maturity according to Monsi and Saeki [35]. Extinction coefficients for sorghum of 0.37 and 0.60 were employed from the literature [36,37]. Daily gross assimilation (Equation (1)) and growth (Equation (2)) and maintenance respirations (Equation (3)) were calculated using the following equations according to Lövenstein et al. [38]. Assimilation efficiency (Ea) and reflection coefficient (p_c) were fixed as 9, i.e., a typical value for C4 crops, and 0.08 respectively. A temperature correction coefficient (TC) was calculated for each day by applying the average temperature on the day. Although the experiments were conducted on two replicates, one replicate that was considered to be an outlier was omitted from calculations when values of the two replicates differed to a large degree, i.e., the value of one replicate was smaller than that of the other by more than 30%.

$$At = Ea \times (1 - p_c) \times It \times \{1 - \exp(-k \times LAIt)\} \tag{1}$$

$$MRt = TC \times \sum(A0 + A1 + A2 + \ldots + At) \tag{2}$$

$$GRt = 0.3 \times (At - MRt) \tag{3}$$

At: daily crop assimilation at day t [kg CO_2 ha^{-1} day^{-1}] (t: day number)
Ea: assimilation efficiency [kg CO_2 J^{-1}]
It: Incident PAR at day t [J ha^{-1} day^{-1}]
p_c: crop reflection coefficient
k: extinction coefficient
LAIt: green leaf area index at day t
MRt: maintenance respiration at day t
TC: temperature correction coefficient
GRt: growth respiration at day t

3. Results

3.1. Weather

Mean daily temperature, total rainfall and total solar radiation during the experiments are presented in Table 4. There was a long dry spell of nearly 50 days in July and August 2013.

Table 4. Mean temperature, total rainfall and total solar radiation over two cropping seasons.

Month	2012			2013		
	Temperature (°C)	Rainfall (mm)	Solar Radiation (MJ)	Temperature (°C)	Rainfall (mm)	Solar Radiation (MJ)
May	18.0	194	597	17.5	49	686
June	19.7	177	565	21.1	110	496
July	25.2	115	593	25.3	43	586
August	27.6	11	663	27.5	61	615
September	24.5	136	449	23.2	154	459
October	17.3	131	375	18.1	429	311
Mean	22.1	127	540	22.1	141	525

3.2. Leaf Area Index (LAI)

LAI observations made at the time of samplings were linearly interpolated (Figure 1). In 2012, the peak of LAI was in the range of 5–6, while it was in that of 8–11 in 2013. LAI tended to decrease very quickly in 2013 due to the severe infestation by aphids. Similarly, to the process of simulation, one

replicate out of the two was omitted from calculations when values of two replicates differed to a large degree, i.e., the value of one replicate was smaller than that of the other by more than 30%, and one was considered as an outlier. The interpolated LAI data obtained here were then used to estimate light interception and biomass yield in the process of simulation.
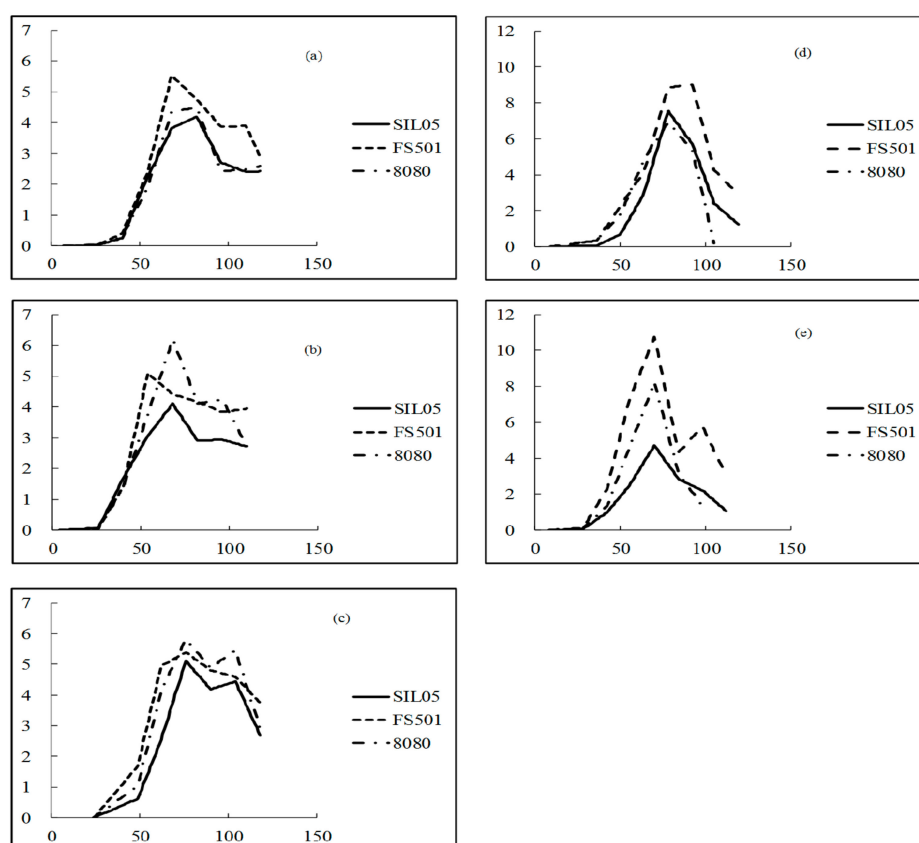
Figure 1. Interpolation of Leaf Area Index (LAI) sown: (**a**) Early (2012); (**b**) Medium (2012); (**c**) Late (2012); (**d**) Early (2013); and (**e**) Medium (2013). X axis: days after sowing (DAS); Y axis: LAI.

3.3. DM Yield and Brix

Height, LAI, effective tiller number, DM yield of different organs, DM content of above-ground part and stem brix are presented in Table 5. Interactions were observed with panicle DM yield, DM content and stem brix. As to panicle DM yield, significant interactions between cultivar × year and sowing × year were observed. In the former interaction, it was greater in 2012 than in 2013 for FS501 and 8080 while no significant difference between two years was recognized for SIL05. In the latter interaction, greater panicle DM yield was observed for early sowing than for medium sowing in 2013, while there was no difference between the two sowing timings in 2012. In DM content, no difference was observed between SIL05 and FS501 for early sowing, while for medium sowing, DM content was higher for SIL05 than FS501. As to stem brix, there was no difference between two years for medium sowing, while a greater value was observed in 2012 than in 2013 for early sowing. There was no difference between SIL05 and FS501 for early sowing, while stem brix values were significantly higher for SIL05 than for FS501 for medium sowing. Effects of sowing dates were hardly seen except for height where greater height was associated with early sowing. FS501 showed greater LAI than SIL05 and 8080. Pearson's correlation analysis revealed that stem brix was negatively correlated with leaf DM yield and panicle DM yield (Table 6) and it was positively correlated with stem DM yield and especially stem DM content.

Table 5. Height, leaf area index (LAI), effective tiller, dry matter (DM) yield, DM content and brix of sorghum at harvest.

Year	Sowing	Cultivar	Height (cm)	LAI	Efftiller (m⁻²)	DM Yield				DM Content	Brix (%)
						LS + Stem (kg·m⁻²)	LB (kg·m⁻²)	Panicle (kg·m⁻²)	Above-Ground (kg·m⁻²)	Above-Ground (%)	
2012	Early	SIL05	325	2.42	13.6	1.31	0.38	0.12	1.82	24.1	12.6
		FS501	318	2.89	11.4	1.08	0.42	0.11	1.61	25.2	13.7
		8080	151	2.59	12.9	0.35	0.47	0.37	1.18	31.0	
	Medium	SIL05	269	2.09	14.3	0.88	0.25	0.12	1.24	24.9	16.2
		FS501	308	3.94	12.9	0.97	0.47	0.33	1.77	22.5	6.1
		8080	141	1.95	10.8	0.22	0.44	0.46	1.12	25.9	
	Late	SIL05	286	2.58	15.7	0.78	0.28	0.08	1.13	20.8	13.0
		FS501	337	3.74	12.9	0.79	0.42	0.19	1.40	18.6	5.2
		8080	146	2.90	15.0	0.20	0.38	0.46	1.04	27.6	
2013	Early	SIL05	309	1.25	11.4	0.64	0.30	0.10	1.04	17.8	5.3
		FS501	329	2.92	15.0	0.92	0.52	0.12	1.56	17.6	3.3
		8080	151	0.19	12.9	0.21	0.42	0.23	0.86	25.8	
	Medium	SIL05	284	1.07	16.4	0.76	0.21	0.05	1.0	21.3	9.6
		FS501	276	3.06	11.5	0.77	0.39	0.05	31.2	16.0	5.8
		8080	131	1.36	15.0	0.15	0.46	0.08	20.70	22.9	

Factor	df	df (Brix)									
Year (Y)	1	1									
Sowing (S)	2	2	ns	**	ns	*	ns	***	*	***	***
Cultivar (C)	2	1	*	ns	ns	ns	ns	ns	ns	**	ns
Y * S	2	2	***	***	ns	***	**	***	*	***	**
Y * C	2	1	ns	ns	ns	ns	ns	**	ns	ns	*
S * C	4	2	ns	ns	ns	ns	ns	*	ns	ns	ns
Block	1	1	ns	ns	ns	ns	ns	ns	ns	*	*
Residual	15	9									
Total	29	19									

Efftiller: Effective Tiller; LB: leaf blade; LS: leaf sheath; df: degree of freedom * Significant at 0.05; ** Significant at 0.01; *** Significant at 0.001.

Table 6. Pearson's correlation analysis between traits over two seasons.

	Leaf Dry Matter (DM) Yield	**Panicle DM Yield**	**Stem DM Content**	**Stem Brix**
Stem DM yield	NS	−0.41 *	0.56 **	0.44 *
Leaf DM yield		0.38 *	NS	−0.45 *
Panicle DM yield			NS	0.46 *
Stem DM content				0.86 **

* Significant at 0.05; ** Significant at 0.01.

3.4. Estimation of Radiation Use Efficiency (RUE)

RUE was estimated by plotting above-ground DM yield against intercepted radiation (Figure 2a,b). Radiation intercepted by the sorghum canopy was simulated from daily solar radiation using an analogue of Beer's law [35,39] for each cultivar in each season. RUE is presented in Table 7. A light extinction coefficient (k) of 0.37 (Figure 2a,b and Table 7) and 0.60 (Table 7) was employed from the literature [36,37]. Greater RUE values were estimated by 13.8–24.4% when a light extinction coefficient of 0.37 was employed compared to 0.60.

(a)

(b)
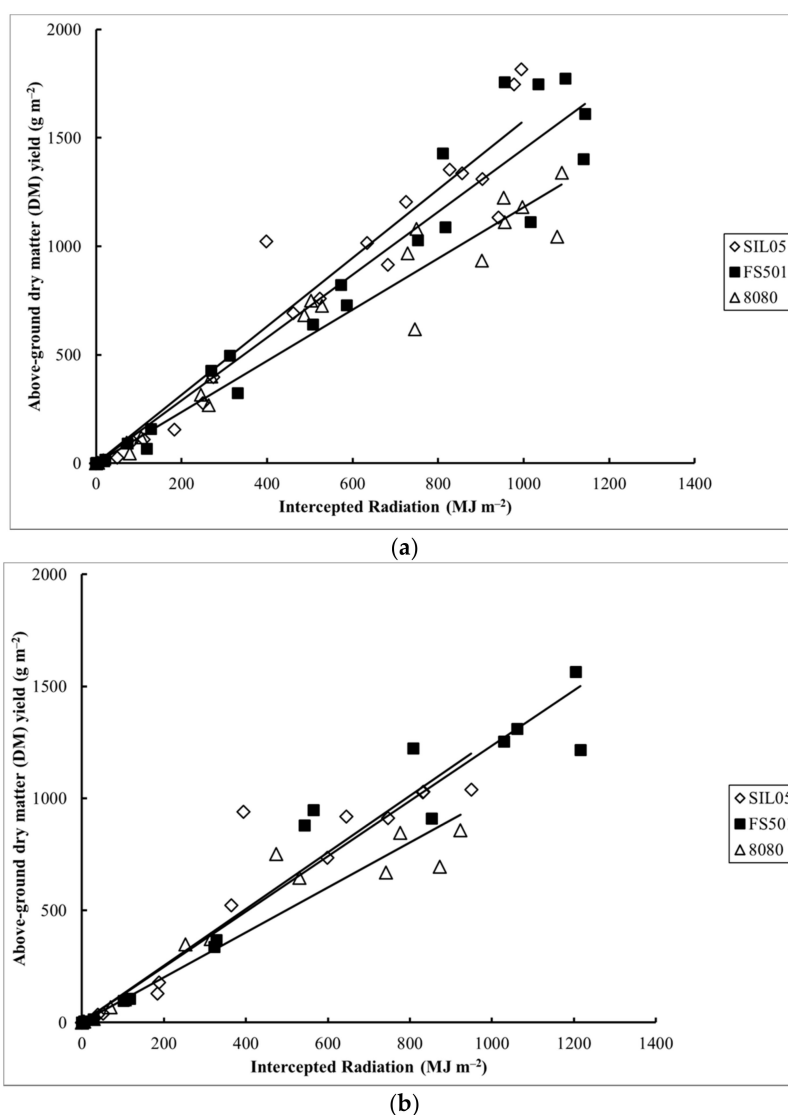
Figure 2. (**a**) The relationship between intercepted radiation and above-ground dry matter (DM) yield in 2012. (**b**) The relationship between intercepted radiation and above-ground DM yield in 2013.

Table 7. Results of regression analysis between interpreted radiation and biomass yield.

Year	k	Cultivar	p	R^2	Coefficient (RUE)	
					p	g MJ^{-1}
2012	0.37	SIL05	<0.001	0.97	<0.001	1.58
		FS501	<0.001	0.97	<0.001	1.45
		8080	<0.001	0.98	<0.001	1.18
	0.60	SIL05	<0.001	0.97	<0.001	1.27
		FS501	<0.001	0.97	<0.001	1.21
		8080	<0.001	0.98	<0.001	0.98
2013	0.37	SIL05	<0.001	0.96	<0.001	1.26
		FS501	<0.001	0.98	<0.001	1.23
		8080	<0.001	0.96	<0.001	1.01
	0.60	SIL05	<0.001	0.96	<0.001	1.03
		FS501	<0.001	0.98	<0.001	1.08
		8080	<0.001	0.96	<0.001	0.85

3.5. Estimation of Biomass Yield

　　Estimated daily assimilation and accumulated assimilation, i.e., yield, were presented as an example of the simulation for the data set of SIL05 sown early in 2012 (Figure 3a,b). The remaining results are presented in Table 8. Net assimilation of FS501 exceeded 20 Mg ha^{-1} for all sowing dates in two years, while that of SIL05 were below 20 Mg ha^{-1} for 5 simulation sets out of 10 (Table 8). The simulated results were plotted against the observed biomass yield (Figure 4). The yield level obtained in the present study was found below the estimated potential (region B in Figure 4) except for in a few cases (region A in Figure 4). Another attempt was made to estimate the potential biomass production of sorghum at different locations from RUE and Water Use Efficiency (WUE) (Table 9). RUE of 1.4 g MJ^{-1} and WUE of 5.0 g kg^{-1} were assumed following Narayanan et al. [40]. In contrast to USA, biomass production was greater when estimated from rainfall than from radiation in most of the locations in Japan except for Takamatsu, which is known for its dry summers, and Tsukuba (Kannondai) in 2012 and 2013, where the present study was conducted.
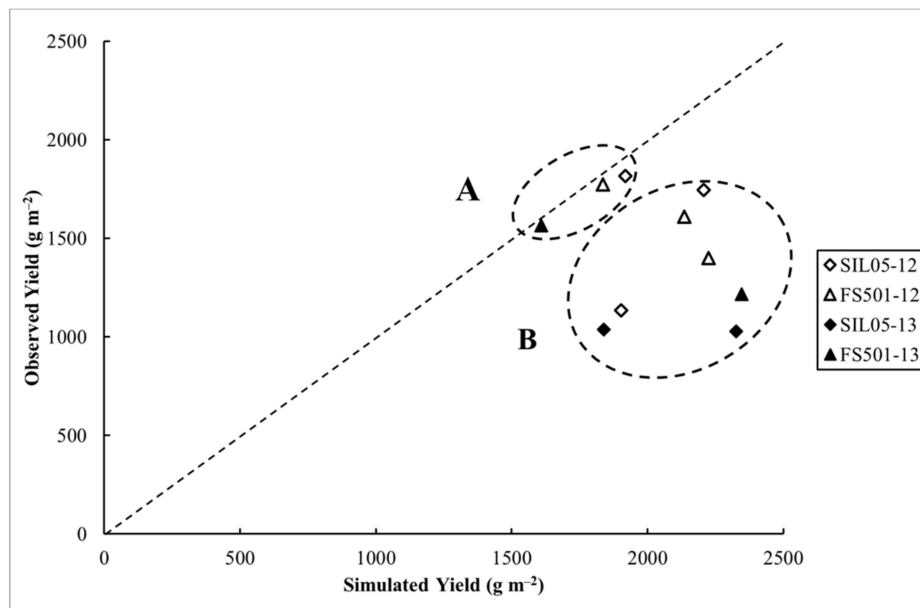

(**a**)

Figure 3. *Cont.*

(**b**)
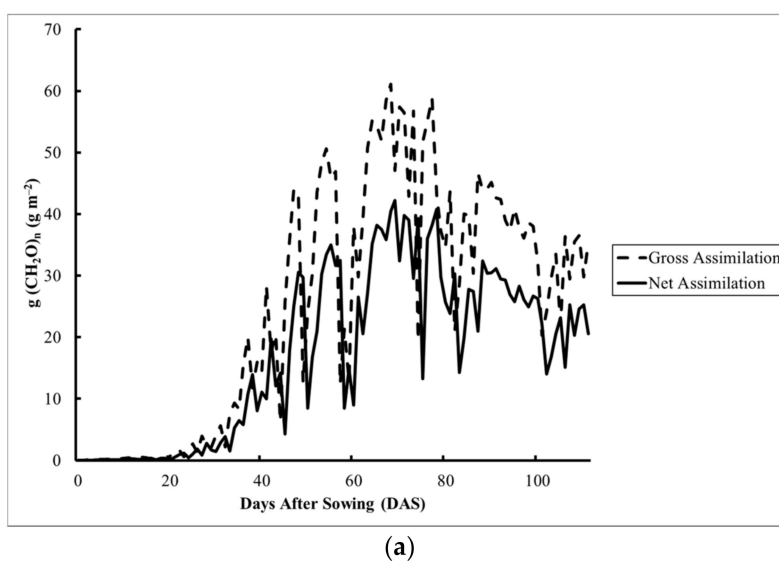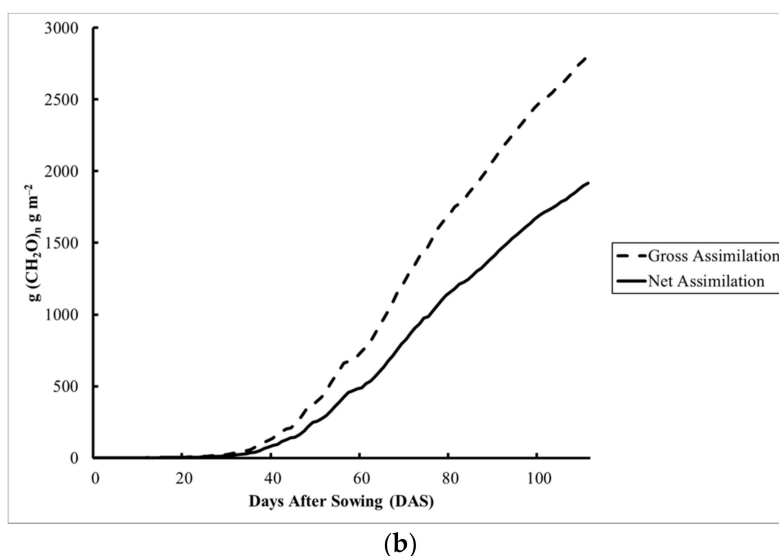
Figure 3. (**a**) Estimated daily gross and net assimilation for SIL05 sown early in 2012. (**b**) Estimated accumulation of gross and daily assimilation for SIL05 sown early in 2012.

Table 8. Simulated gross assimilation, respiration and net assimilation.

Year	k	Sowing	Cultivar	Gross Assimilation g $(CH_2O)n\ m^{-2}$	Respiration g $(CH_2O)n\ m^{-2}$	Net Assimilation g $(CH_2O)n\ m^{-2}$
2012	0.37	Early	SIL05	2808	890	1918
			FS501	3228	1022	2206
		Medium	SIL05	2758	857	1902
			FS501	3098	963	2136
		Late	SIL05	2657	821	1835
			FS501	3219	995	2224
	0.60	Early	SIL05	3521	1117	2405
			FS501	3857	1222	2635
		Medium	SIL05	3464	1076	2389
			FS501	3689	1146	2543
		Late	SIL05	3233	1000	2233
			FS501	3806	1177	2629
2013	0.37	Early	SIL05	2681	842	1840
			FS501	3400	1075	2326
		Medium	SIL05	2347	738	1609
			FS501	3433	1088	2345
	0.60	Early	SIL05	3209	1011	2199
			FS501	3888	1231	2657
		Medium	SIL05	2996	944	2052
			FS501	3858	1226	2632

Figure 4. Comparison between simulated and observed yield: (A) the plots where the simulated yield was close to the observed yield; and (B) the plots where the simulated yield was higher than the observed yield.

3.6. Estimation of Ethanol Yield

Ethanol yield was estimated using stem yield and brix obtained in the present study following methodologies from the literature [20,25,41] (Table 10). Estimated ethanol production exceeded 2000 L ha^{-1} for SIL05 and FS501 with early sowing as well as SIL05 with medium sowing in 2014. With late sowing in 2014 and early and medium sowing in 2015, estimated ethanol production was generally low.

Table 9. Estimation of biomass production of sorghum from solar radiation and rainfall.

Region/Country	Location	Latitude (°N)	Year			Temperature (°C)	Radiation (MJ m^{-2})	Rainfall (mm)	Estimated Biomass Production (Mg ha^{-1})	
			Temperature	Radiation	Rainfall				Radiation	Rainfall
the Kanto region	Tsukuba (Kannondai)	36.02		2012		23.0	2867	633	40.1	31.7
				2013		22.9	2842	417	39.8	20.8
	Tsukuba (Tateno)	36.03		1981–2010 [†]		21.7 [†]	2418 [†]	694 [†]	33.8	34.7
	Utsunomiya	36.33		1981–2010 [†]		21.9 [†]	2181 [†]	957 [†]	30.5	47.9
	Choshi	35.44		1981–2010 [†]		21.5 [†]	2599 [†]	751 [†]	36.4	37.5
	Tokyo	35.41		1981–2010 [†]		23.6 [†]	2179 [†]	837 [†]	30.5	41.9
the Shikoku region	Takamatsu	34.20		1981–2010 [†]		24.3 [†]	2653 [†]	637 [†]	37.1	31.9
the Nansei region	Naha	26.13		1981–2010 [†]		27.2 [†]	2795 [†]	1122 [†]	39.1	56.1
USA	Nebraska	41.98	1961–1990 [‡]		2007–2008 [a]	20.3 [‡]	3229 [‡]	245–563 [a]	45.2	12.3–28.2
	Illinois	39.83	1961–1990 [‡]		2009–2010 [b]	21.5 [‡]	3151 [‡]	307–876 [b]	44.1	15.4–43.8
	Louisiana	30.53	1961–1990 [‡]		2010–2011 [c]	26.4 [‡]	2964 [‡]	357–727 [c]	41.5	17.9–36.4

Data source: [†]: Japan Meteorological Agency; [‡]: National Renewable Energy Laboratory. [a] Wortmann et al., 2010 [20]; [b] Maughan et al., 2012 [42]; [c] Han et al., 2012 [24].

Table 10. Estimation of ethanol yield and production by three methods.

Year	Sowing	Cultivar	Wortmann et al. (2010) [20]		Zhao et al. (2012) [25]		Okinawa General Bureau (2010) [41]	
			Ethanol Yield (L Mg^{-1} FS *)	Ethanol Production (L ha^{-1})	Ethanol Yield (L Mg^{-1} FS *)	Ethanol Production (L ha^{-1})	Ethanol Yield (L Mg^{-1} FS *)	Ethanol Production (L ha^{-1})
2012	Early	SIL05	42–44	2421–2970	34–35	1958–2333	35–36	2033–2421
		FS501	45–49	2187–2458	36–39	1770–1934	38–40	183–2008
	Medium	SIL05	56	1015–3487	43–46	827–2712	45–47	859–2815
		FS501	17–24	901–1404	14–20	707–1139	14–20	734–1182
	Late	SIL05	40–52	1631–1997	31–40	1275–1552	32–42	1323–1612
		FS501	15–22	690–1365	12–17	540–1049	12–17	561–1089
2013	Early	SIL05	15–22	782–818	12–17	602–639	12–18	625–663
		FS501	11–12	712–801	8–10	553–626	9–10	574–650
	Medium	SIL05	24–42	804–1871	20–33	661–1455	20–341	686–1511
		FS501	15–27	1041–1141	12–20	762–895	2–21	791–929

* Fresh stalks.

4. Discussion

4.1. Yield and Brix

As mentioned in the Introduction, Inuyama et al. [27] obtained stem weights of sorghum in the range of 3.37–4.48 kg m^{-2} on a fresh matter basis. These values are comparable to the lower range of the values obtained in the present study, i.e., 3.35–7.56 kg m^{-2}. To compare yield levels obtained in the present study in terms of those reported by other workers, DM yield was plotted against DM content (Figure 5a,b) [20,43,44]. Compared on a DM basis, yields obtained in the present study were relatively lower than those reported by Wortmann et al. [20] (Figure 5a) and Fukazawa et al. (Figure 5b) [43], while they were comparable to those reported by Harada et al. (Figure 5b) [44]. High values of DM content reported by Wortmann et al. [20] and Fukazawa et al. [43] appeared to explain at least partly the differences in DM yield between their studies and the present study (Figure 5a). As to stem brix, Kamiyama et al. [45] observed values in the range of 13.7% to 16.2% for three cultivars in Ibaraki prefecture, while stem brix in the present study and especially of FS501 was generally lower. Kawahigashi et al. [46] reported brix values ranging from 2.8% to 19.6% for 109 sorghum accessions where SIL05 showed a value as high as 19.4% compared to the range of 5.3% to 16.2% observed in the present study for the same cultivar. When plotted against DM content, stem brix was positively correlated to DM content (Figure 5c) [20,43], which was in accordance with Table 6.
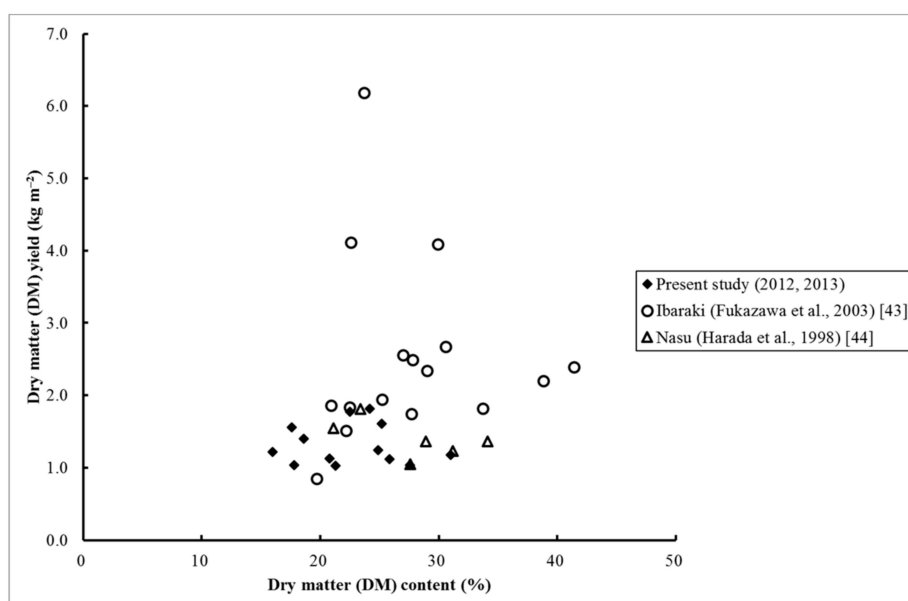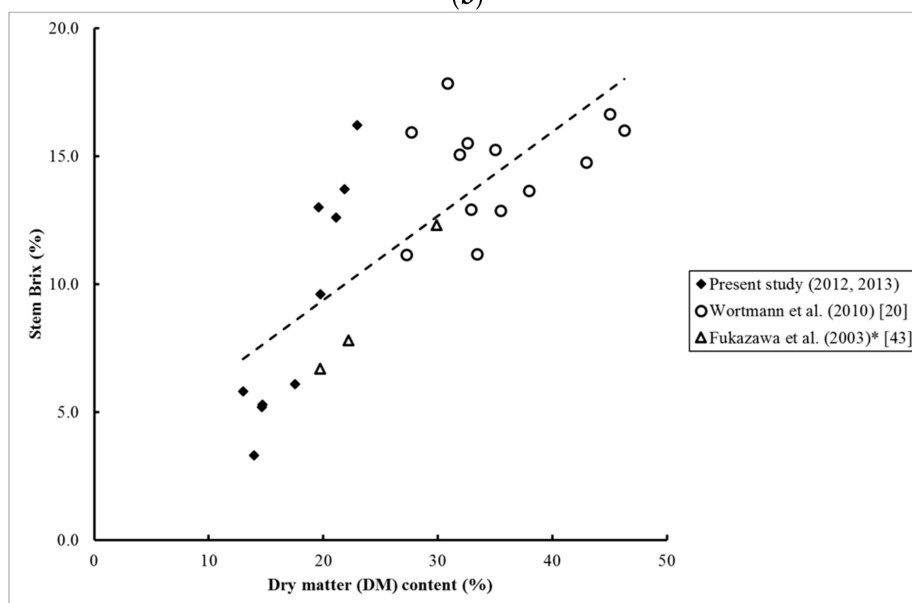

(**a**)
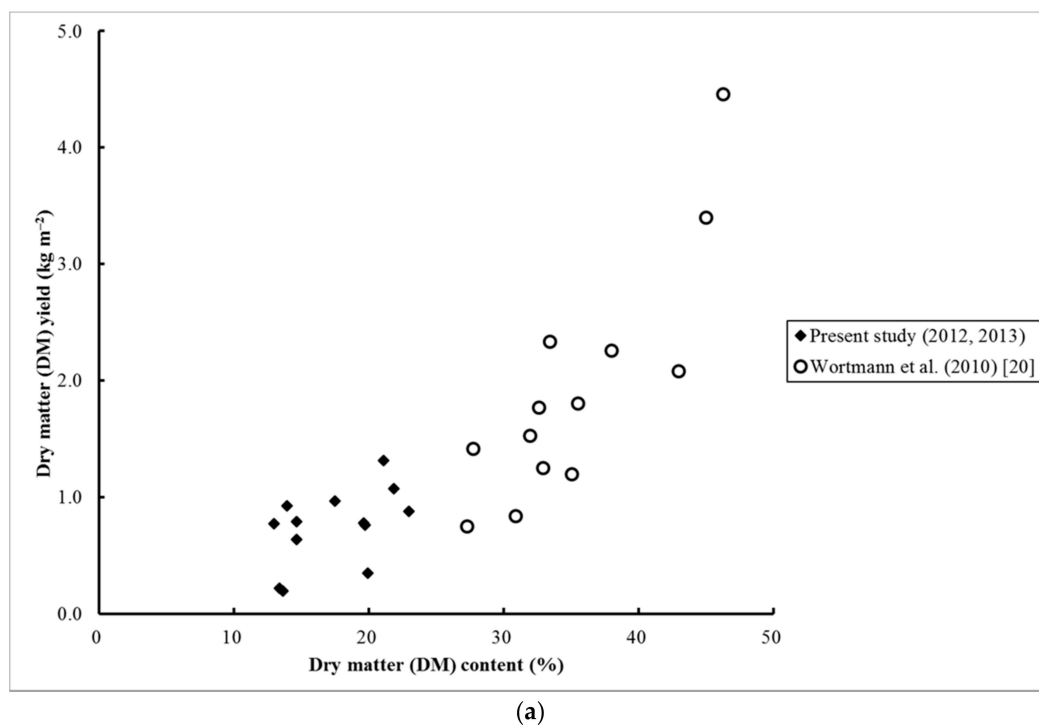
Figure 5. *Cont.*

(b)

(c)

Figure 5. (**a**) The relationship between stem dry matter (DM) content and stem DM yield. (**b**) The relationship between above-ground DM content and above-ground DM yield. (**c**) The relationship between stem DM content and stem brix. * The relationship between above-ground DM content and stem brix.

4.2. RUE

RUE estimated in the present study was in the range of 1.01–1.58 g MJ^{-1} solar and 0.85–1.27 g MJ^{-1} solar for light extinction coefficient of 0.37 and 0.60, respectively. In the case of 8080, leaves are arranged along a short statue, while the number of leaves is not very different from that of SIL05 and FS501. This might explain the smaller RUE obtained with 8080 compared to other cultivars. Monteith [47] pointed out that at least during the vegetative stage, the relationship between intercepted radiation and the annual production of DM was surprisingly similar for barley, potatoes, sugar beet and apples and showed that the slope, RUE, would be approximately 1.4 g MJ^{-1} solar in the UK. Values between 1.10 and 2.16 g MJ^{-1} solar have been cited for sorghum [48]. Hammer et al. [36] obtained RUE in the

range of 1.19–1.84 g MJ^{-1} solar for dwarf sorghum. Horie and Okada [49] reported RUE of 2.75 g MJ^{-1} PAR (Photosynthetically Active Radiation) with rice until maturation. Their calculation, however, included root biomass, which was not assessed in the present study. In a recent study with sorghum in Northern Italy (44°32′N, 11°11′E, 38 m a.s.l.), Ceotto et al. [37] obtained RUE of as high as 3.48 g MJ^{-1} PAR where above-ground DM yield was plotted against intercepted PAR. Similarly in Kansas State, USA (39°24′N, 101°4′W, 963 m a.s.l.), Narayanan et al. [40] obtained RUE in the range of 2.13 to 3.53 g MJ^{-1} PAR. Values of 1.4 g MJ^{-1} solar and 2.0 g MJ^{-1} solar were reported [50] for C3 and C4 species, respectively, grown under optimum conditions. Bearing these values in mind, RUE obtained in the present study was considered relatively low for sorghum suggesting room for improvement in cultivation.

4.3. Estimation of Potential Yield and Ethanol Yield

An attempt was made to simulate potential yield of sorghum in the present study. As the LAI data set used was the one obtained in the present study, one needs to be aware that potential yield here means the one restricted by the observed LAI. The observed yields were found to be below the simulated yields especially in 2013 implying that the photosynthetic ability of green leaves was likely to be impaired to some extent. Possible factors we can think of are limited precipitation as well as the infestation by aphids. Pronounced effects of both factors such as rolling of leaves and leaves covered by black sooty mold on the aphid honey dew were observed especially in 2013. The LAI values observed in their peak in the present study appeared comparable to or even greater than the values reported by Narayanan et al. [40], which is interesting considering that some of the genotypes in their study produced above-ground DM yield greater than 2000 g m^{-2}. It should be noted that in the present study, estimation was conducted in a quite simplified manner without differentiating the vegetative phase from the reproductive phase. Besides, respiratory costs associated with sugar accumulation in the stem during the later phase of growth could complicate the balance sheet of assimilates in sorghum, in a similar way to sugarcane. In Table 9, a simple estimation of potential DM yield from weather data was attempted to evaluate the climatic resources of different places to produce sorghum. Solely from the perspective of solar radiation, one might be able to expect production of 30 to 40 Mg ha^{-1} of biomass yield in the Kanto region, a slightly lower level compared to that in USA, although it would be very much influenced by precipitation during the growth period. Both in 2012 and 2013 of the present study, potential yield was suppressed greatly by the amount of rainfall. In 2013 in particular, only a half of production estimated from solar radiation was considered to be theoretically possible. The issue of dry summer experienced in the study area will be further discussed later. As brix was generally low in the present study, the potential ethanol yield was low compared to the values reported in the literature [20,25].

4.4. Implication for Field Management

4.4.1. Seed Rates and Weeds Infestation

It was possible to reduce the amount of sorghum seeds needed for sowing by 80–90% using a pneumatic seeder. A small plot experiment conducted in 2013 (data not shown), however, indicated that the use of a power harrow seeder might be a better way of sowing sorghum in terms of early crop growth and increased competition with weeds for resources even though one needs more seeds with this machinery. The issue of crop establishment requires further examination. Digitaria (*Digitaria ciliaris* (Retz.) Koel.), spotted lady's–thumb (*Persicaria maculosa* Gray), white goosefoot (*Chenopodium album* L.), and Amaranthus retroflexus (*Amaranthus viridis* L.) dominated some of the plots and appeared to have affected the growth and yield of sorghum in both years (data not shown). When sown in the middle of May, it took a week for sorghum seeds to germinate compared to 4–5 days in June. This, combined with slow growth of sorghum during the early growth phase which is sometimes compared with maize [51], is likely to allow weeds to establish faster than the crop. Sorghum originates from

semi-arid tropics [52] and one cannot deny that temperature in the Kanto region is too low to exploit the yielding ability of this crop to its full capacity. Low temperature during the early phase of growth up to canopy establishment, a similar situation with sugarcane in southwest islands [53,54], is one of the main factors limiting yields. It appears that, in this region, when sowing sorghum as early as the middle of May, a cultivar possessing the trait of faster early phase growth would be required to compete effectively with weeds.

4.4.2. Aphids

Aphids were present in both years. In 2013, an outbreak was observed from early August until late August when it was stopped with the event of rainfall. Setokuchi [55] pointed out that dry weather and high temperature are the factors that favor growth of aphids (*Longiunguis sacchari* (Zehntner)). He reported a reduced DM content of sorghum following the infestation by this pest. As previously mentioned, values of DM content in the present study were found to be generally low compared with those reported in other studies. As a positive correlation was observed between DM content and stem brix, it is possible that stem brix was negatively affected by the presence of aphids. When one looks at mean temperature over last 30 years [56], maximum temperature in August in Tsukuba is lower by approximately 2 °C than that in Tadotsu, Kagawa, a prefecture known within Japan for its hot and dry summers. Similarly, the amount of rainfall during summer in Tsukuba is greater than that in Tadotsu. Weather data in 2012 and 2013 [56] however tell us a different story. There was almost no difference between the two locations in maximum temperature, while precipitation in summer was less in Tsukuba than in Tadotsu indicating that the weather conditions in Tsukuba were more likely to favor aphids. Evidence from the present study suggests that it is important to control aphids in sorghum during this growth phase and that the aspect of aphids needs to be investigated further, as this could be one of the major issues affecting the successful cultivation of sorghum in the Kanto region.

4.4.3. Typhoons

In 2012, two typhoons affected the field experiment. The first one was in June and only caused some leaf damage. High ridging was considered to have saved the seedlings from lodging. The second typhoon was at the end of September, and almost completely knocked down the cultivars of more than 3 m in height. i.e., SIL05 and FS501. The number of typhoons that have come close to the Kanto region in last 20 years is much fewer than to Okinawa, one of the most vulnerable regions to typhoons in the country (Figure 6) [56], however, it is probably optimistic to expect no typhoons to affect the Kanto region during the period from May to September. From the perspective of minimizing the risk of lodging, it is preferable that sorghum of a high growth habit be harvested by early September. In this respect, it might be better to place sorghum of a shorter growth habit such as 8080, which survived the typhoon at the end of September, after wheat or barley in the sequence of crop rotation, as harvesting wheat and barley would occur usually in June in this part of the world.
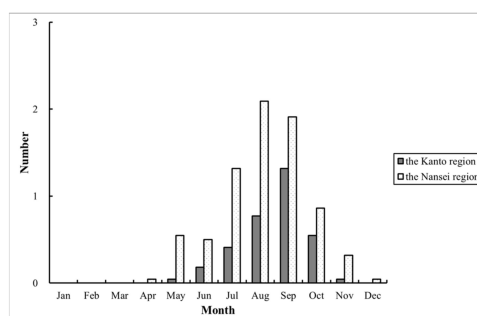
Figure 6. The average number of typhoons that had come close to the Kanto and the Nansei region in last 20 years.

4.4.4. Future Perspective

Other issues to be looked into are the nutrient management of sorghum for biomass usage as well as preservation of the crop. As to the former issue, excess nitrate accumulation in feed crops including sorghum [44], very often being the consequence of overdosed fertilizer and/or manure application [57], has been regarded as a factor that can cause serious health problems with livestock. However, fertilizer recommendation rates for feed sorghum vary for prefectures with the differences sometimes exceeding twofold [58]. It is of importance therefore, from the perspective of nutrient recycling and energy saving [22], that the wastes from the neighboring ethanol plants such as vinasse should be utilized as crop fertilizers. The latter issue of preservation is worth studying, because the stem juice of sorghum is known to deteriorate rather quickly after harvest [59], which is a possible factor that could hinder the use of sorghum as a feedstock. In addition, in the view of completing the cropping system as a whole, the inclusion of high yielding winter crops [60] would be an essential component to be considered in future studies. Poor early growth observed with the plots sown on 13 May, 2013 was considered to be at least partly attributable to possible allelopathic effects of oat residues [61] especially roots [62] as all the above-ground parts of oat had been removed from the field prior to sowing sorghum. Sown after oat as well, early growth of sorghum sown on 28 May 2013 did not appear to have been affected by the previous crop to the extent observed with the crop sown two weeks earlier. The issue of allelopathy would probably require a further examination to establish cropping systems that could support sustainable biomass production in the target region. Maize cultivation could be a possible alternative to avoid continuous sorghum cropping. A large part of the issues discussed above could probably not be solved solely by improving agronomy. Multiple cultivars are required if one wants to run any cropping system in sustainable manner. To cultivate sorghum in the Kanto region especially within a global warming context, more cultivars, for example, preferably with early vigor and equipped with resistance to aphids need to be developed.

5. Conclusions

Sorghum seeds of both sweet sorghum (SIL05 and FS501) and grain sorghum (8080) cultivars were sown under two field experiments conducted in 2012 and 2013 to estimate yielding ability of this crop in the Kanto region in the context of bioethanol production. Above-ground DM yield in the range of 1.03–1.82 kg m^{-2}, 1.22–1.77 kg m^{-2} and 0.70–1.18 kg m^{-2} were obtained for SIL05, FS501 and 8080, respectively, in two years. The yield level obtained in the present study was found below the estimated potential except for in a few cases. In contrast to USA, potential biomass production was greater when estimated from rainfall than from radiation in most of the locations in Japan. Observed yields, however, were greatly suppressed by the amount of rainfall in both experimental seasons in the study site. As brix was generally low in the present study, the potential ethanol yield was low compared to the values reported in the literature. A positive correlation observed between DM content and stem brix suggests a possibility that stem brix was negatively affected by the presence of aphids. Controlling the population of aphids was identified to be one of the crucial factors determining the successful cultivation of sorghum in the Kanto region.

Author Contributions: Shoko Ishikawa and Ken-ichi Yakushido conceived and designed the experiments; Shoko Ishikawa, Takayuki Tsukamoto, Hitoshi Kato and Kazuto Shigeta performed the experiments; Shoko Ishikawa analyzed the data; Shoko Ishikawa contributed reagents/materials/analysis tools; and Shoko Ishikawa wrote the paper.

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