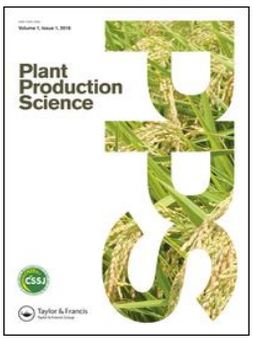

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A mechanical study on the mitigation of lodging in edible canna

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ABSTRACT

Because edible canna is approximately 3-m tall in its latter growth stage, strong winds such as by typhoons can induce plant lodging and cause severe damage to it. To improve our previous estimations that the 1-m dwarfing of a plant mitigated 10–20% by strong wind (external force) and 50% by own weight (internal force), respectively, we re-examined these parameters in relation to rhizome yield for field-grown plants. From early middle growth stage (July–August) of edible canna, the perpendicularly projected area of above-ground biomass increased rapidly due to rapid shoot elongation. After the middle growth stage (September), the stock base radius increased and shoot inclination angle decreased until the latter growth stage (November) gradually, indicating a disturbed architecture and easy lodging. Throughout the growth period, we observed no radial, directional difference in the leaf area distribution. Increase in the distance between the ground surface and the center of gravity of shoot weight and decrease in the shoot inclination increased the components of the internal force. The easiness to fall down (percentage own-weight invasion moment) of plant became maximal in the latter growth stage. We conclude that approximately 50-cm dwarfing of the plant with minimal loss of rhizome yield (as low as approximately 20%) and the maintenance of lodging tolerance is optimal. In such a situation, both external and internal forces are mitigated by approximately 30%.

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Canna edulis; external force; internal force; own-weight moment; projected area; yield

CLASSIFICATION
Agronomy & Crop ecology

1. Introduction

Edible canna is a prospective plant resource that is domesticated in Andean Regions (Gade, 1966; Ugent et al., 1984). Presently, it is cultivated on a small scale at scattered locations in sub-tropical to tropical areas without intensive breeding, and it is used for several purposes such as direct food, animal food, a source material of starch, and local medicine (Imai, 2011, 2014; National Research Council, 1989; Roth & Lindorf, 2002). The net photosynthetic rate of edible canna is moderately high among C_3 species (Imai & Ichihashi, 1986; Kato & Imai, 1996), and its potential productivity is thought to be very high (Imai et al., 1993, 1994; Yamamoto et al., 2010).

Although the superior structure and physical characteristics of roots (Hosoi & Imai, 2002) and the mushroom shape of the root system well support its tall and heavy stand with a high leaf area index (Hosoi & Imai, 2003), edible canna is intolerant to strong winds and heavy rains when low-pressure systems (e.g. typhoons) pass through during its latter growth stage (Imai et al., 1994). Based on our mechanical studies, important causal factors of lodging were determined to be the large projected area (mostly composed of leaves), which is acted upon by external forces such as wind, and the own-weight moment, which is affected by the internal force of its heavy aerial weight (Hosoi & Imai, 2004). In edible canna, the types of lodging include fallen-down, stem-bending, and stem-breaking, as reported for rice (Miyasaka, 1970) and maize (Minami & Ujihara, 1991; Figure 1). Reduction of plant height is a practical strategy for protecting plants from lodging. We previously evaluated plant architecture in terms of leaf area, internal force by own shoot weight, and external force by wind. The results indicated that a desirable plant height at the latter growth stage was about 2 m (about 33% shorter than the original height), which mitigated about 10–20% of the external force by decreasing the projected area and internal force by about 50% (Hosoi & Imai, 2004). However, the results did not indicate how much decreased the rhizome yield. Moreover, from our experiences of edible canna cultivation at field sites, 1 m of shortening seemed too severe to maintain a high level of productivity.

In the present experiment, therefore, we re-evaluated the external and internal forces in relation to yield loss. By choosing related parameters and using regression equations with higher correlation coefficients, we calculated the appropriate plant height with minimum sacrifice of the expected rhizome yield.

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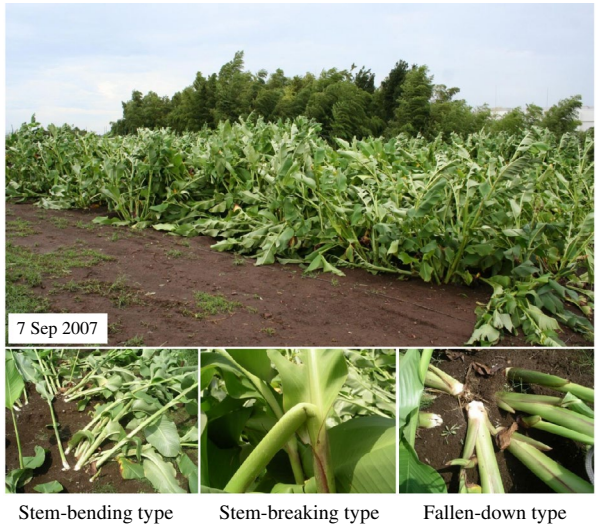

Figure 1. Lodging of edible canna induced by typhoon strike.

2. Materials and methods

2.1. Plant materials

On 21 April 2007 and 20 April 2008, seed rhizomes (ca. 200 g *FW*) of edible canna (*Canna edulis* Ker-Gawl., a green colored local accession from Tanega-shima, Japan) were planted with a wide spacing (2 m × 2 m) at the experimental field of Ikuta Campus, Meiji University (139° 32′ 56″ E, 35° 36′ 48″ N). Just before planting, a compound chemical fertilizer (N, 8%; P_2O_5, 8%; K_2O, 8%) was applied at a rate of 75 g m^{-2} as a basal application. Plants were cultivated under rain-fed conditions with appropriate weeding by hand and without additional fertilizer. Meteorological data (solar radiation, air temperature, and rainfall) were recorded at the experimental site and expressed as 10-day averages, as shown in Figure 2.

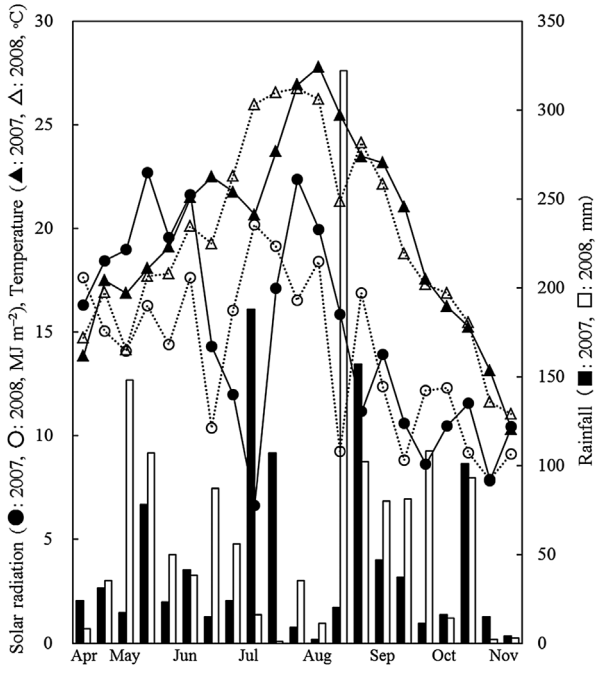

Figure 2. Mean daily solar radiation and temperature, and rainfall per 10 days during edible canna growth periods in 2007 and 2008.

2.2. Measurement and calculation of plant attributes

On 6–8 July, 17–19 August, 28–30 September, and 9–11 November in 2007 and 11–12 July, 18–19 August, 26–28 September, and 1–3 November in 2008, the 'external force' (the wind force on their shoots) and 'internal force' (generated by the plant's own weight) were measured for each of 10 medium-sized plants.

2.2.1. External force

2.2.1.1. Projected area. The external force (units: N, Newton) exerted on the plant body by wind can be expressed as

$$F = \frac{\rho v^2}{2} \times C_d \times S, \quad (1)$$

where ρ is air density (units: kg·m^{-3}), v is wind speed (unit: m s^{-1}), C_d is a resistance coefficient (reflecting the pliability of the plant depending on species, form, and wind speed), and S is the perpendicularly projected side-view area of the plant (units: m^2) that receives wind (Karizumi, 2010). As an important component of F, we investigated the role of S in the present experiment. In general, S has a three-dimensional structure (Shi-igai, 1993); however, we simplified it to two dimensions. The S values of the aboveground parts (leaves and stems), which show growth vigor, are very large during the latter growth stage of edible canna and are determined by three parameters (plant height, width of stock base, and stand angle). To proceed evaluations, we first compared the 'measured projected side-view area (S_{mea}, units: m^2)' and the 'calculated projected side-view area (S_{cal}, units: m^2).' Here, each of S_{mea} and S_{cal} is comparable to S by multiplying by 2.

(a) S_{mea}: We took digital photographs from four directions (north [0 rad], northeast [.785 rad], east [1.571 rad], southeast [2.356 rad]) by arranging a scale (.3 m × .3 m styrene board) beside the plants. The photographs were uploaded to a computer and cutting of the plant images was conducted using graphic software (Adobe Photoshop 6.0, Adobe Systems Inc., San Jose, U.S.A.). The images were black-colored on a white background and divided into two portions at the center point of the stock base. Based on these images, S_{mea} was obtained using area-estimation software (LIA for Win32, by K. Yamamoto, Nagoya Univ., Nagoya, Japan).

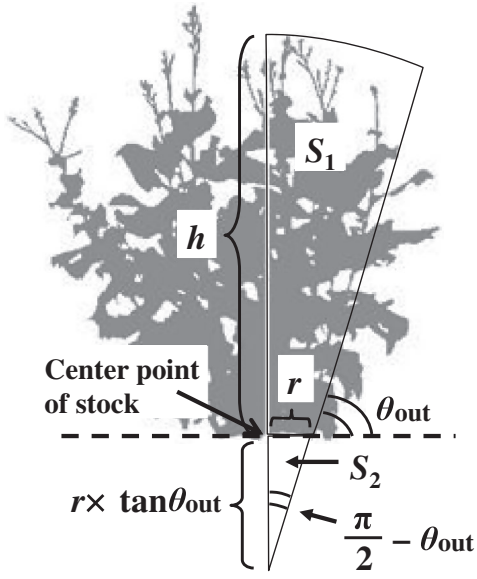

Figure 3. Projected side-view area and basic parameters to calculate 'calculated projected side-view area (S_{cal})'.
Notes: *h*: plant height, *r*: stock base radius, θ_{out}: inclination angle between outmost shoot and ground surface, $S_1 + S_2$: area of fan shape, S_1: temporary calculated projected side-view area, S_2: area of right-angled triangle under ground surface.

(b) S_{cal}: As shown in Figure 3, the plant material tends to spread exterior and a sector (fan shape: $S_1 + S_2$) from the virtual point can be obtained: the fan shape begins underground and passes through the centerline of the stock to the terminal point of plant height (Hosoi & Imai, 2004). At first, we obtained S_1 (= temporary S_{cal}) by subtracting the area of a right triangle (S_2) from the sector. For the calculations, we measured the plant height (*h*, units: m), stock base radius (*r*, units: m), and inclination angle between the outmost shoot and the ground surface (θ_{out}, units: rad, $0 \le \theta_{out} \le \frac{\pi}{2}$). After the calculation of the temporary S_{cal} value on the right side of Equation (2) (without *K*), we plotted the temporary S_{cal} and corresponding S_{mea} values (Figure 4). The linear regression coefficients *K* were regarded as correction coefficients. We applied these to Equation (2) and obtained S_{cal}:

$$S_{cal} = K \times \left\{ \pi \times \left(h + r \times \tan\theta_{out}\right)^2 \times \frac{\frac{\pi}{2} - \theta_{out}}{2\pi} - \frac{r^2 \times \tan\theta_{out}}{2} \right\}. \quad (2)$$

2.2.1.2. Evaluation of projected side-view area distribution. The plant form develops vertically during July and August (early mid-growth stage) due to rapid shoot elongation, and it develops horizontally after September (mid-growth stage) due to the shoot inclination caused by its own weight increment and rhizome swelling. Especially after September, the plant form tends to be disturbed, and the distribution of the side-view area becomes unbalanced; thus, lodging is

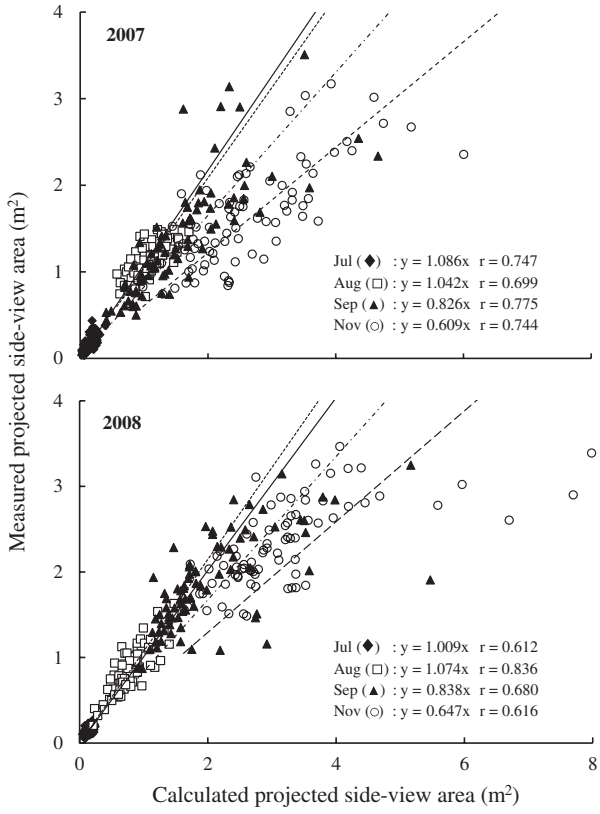

Figure 4. Relationship between calculated projected side-view area and measured projected side-view area of edible canna cultivated in 2007 and 2008.

easily induced. In the present experiment, we examined the distribution of the projected side-view area during the four growth stages of edible canna (with reference to the quantitative evaluation of soybean form by image analysis; Ninomiya & Shigemori (1991)).

(a) *XD* (Figure 5(A)): This parameter shows the distance between main axis taken at the center point of stock width and mean position of vertically sectioned canopy frequency (unit: m). Converted plant images used for the measurement of the projected side-view area were vertically split into 20 sections (numbered 1–20 from left to right), and the number of section pixels *fx*(*i*) was counted using graphic software (Adobe Photoshop 6.0, Adobe Systems Inc., San Jose, U.S.A.). Thereafter, the frequency distributions of the proportion of pixels for individual to total sections *Fx*(*i*) were calculated as follows:

$$Fx(i) = \frac{fx(i)}{\sum_{i=1}^{20} fx(i)}, \quad (3)$$

The center point of a stock in the projected side-view was fixed as the main axis. The plant height (*h*, units: m), the stock breadth (*b*, units: m), and the distance between the main axis and the left side of the stock (*AXS*, units: m)

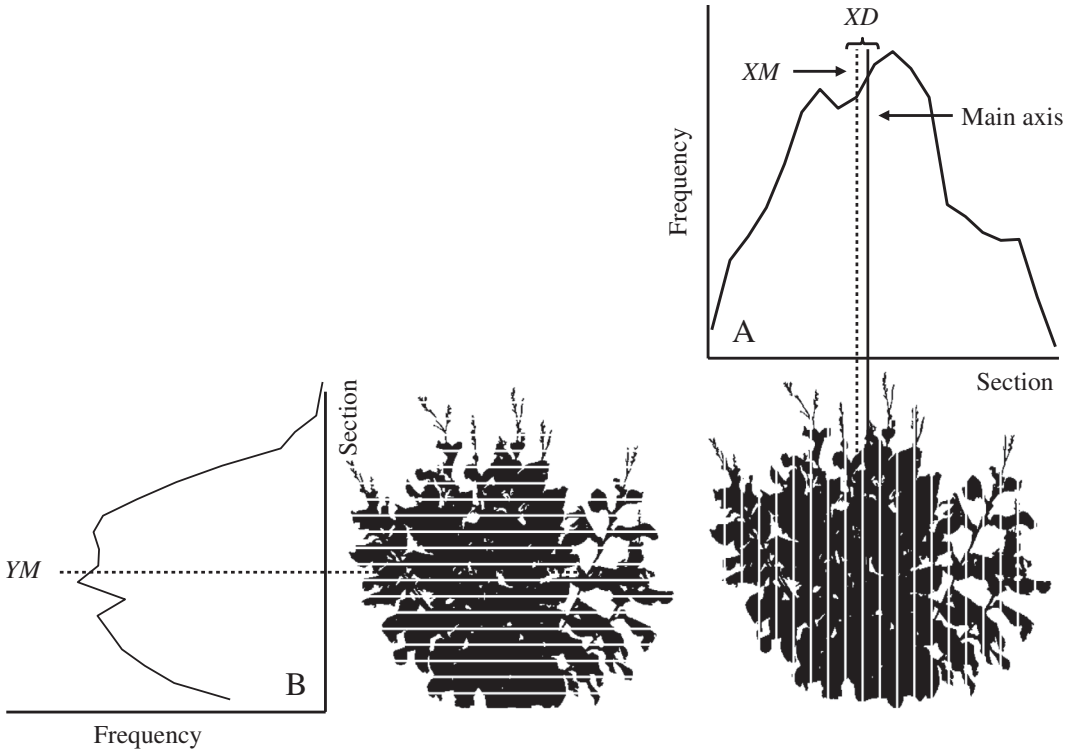

Figure 5. Sectional distributions of projected side-view area of edible canna.
Notes: *XD*: distance between main axis and *XM*. *XM*, *YM*: mean position of canopy frequency sectioned vertically (A) and horizontally (B).

were calculated using area estimation software (LIA for Win32, by K. Yamamoto, Nagoya Univ., Nagoya, Japan). Because *XD* (units: m) changes markedly during growth, we transformed *b* by fixing *h* to 1 m for all of the plants and normalized it as *b**:

$$b^* = \frac{b}{h}, \tag{4}$$

Based on the calculated *b**, the mean position (*XM*, units: m) was calculated by summing the products of each sectional *Fx*(*i*) and the distance between the left side of the stock and the center point of each section, as follows:

$$XM = \sum_{i=1}^{20} b^* \times \frac{\left(i - \frac{1}{2}\right) \times Fx(i)}{20}, \tag{5}$$

XD was calculated by taking absolute values of (*XM* – *AXS*).

(b) *YM* (Figure 5(B)): This shows the mean position of horizontally sectioned canopy frequency (unit: m). Converted plant images used for the measurement of the projected side-view area were horizontally divided into 20 sections (numbered 1 to 20 from bottom to top), and the number of section pixels *fy*(*i*) was counted using graphic software (Adobe Photoshop 6.0, Adobe Systems Inc., San Jose, U.S.A.). Thereafter, as in the case of *XM*, frequency distributions of the proportions *Fy*(*i*) of pixels in the individual sections to the total number of pixels were calculated as follows:

$$Fy(i) = \frac{fy(i)}{\sum_{i=1}^{20} fy(i)}, \tag{6}$$

Because *h* was fixed at 1 m, we calculated the mean position in terms of *YM* using the following equation:

$$YM = \sum_{i=1}^{20} \left(i - \frac{1}{2}\right) \times \frac{Fy(i)}{20}. \tag{7}$$

2.2.2. Internal force

The internal force (units: N) exerted by the shoot weight can be expressed as

$$M_{shoot} = W_a \times L \times \cos\theta, \tag{8}$$

where W_a (units: N) is the static load of the above-ground parts, *L* is the distance (units: m) between the ground surface and the center of gravity of the shoot, and θ (units: rad) is the angle between the ground surface and shoot (*i.e.* the shoot inclination angle; Hozyo, 1976). The W_a value was obtained by weighing cut shoot after taking photographs for S_{mea}. The *L* value was obtained by measuring the shoot lengths and fresh weights of 20 shoots cut from plants that were not used for M_{shoot} (units: N m) measurement. The θ value was measured with a protractor. The own-weight moment for a stock (M_{stock}, units: N m) was also obtained by summing all the M_{shoot} values within a stock. Then, the maximum inversion moment of M_{shoot} or M_{stock}

Table 1. Changes of parameters related to the external force on edible canna cultivated in 2007 and 2008.

	July				August				September				November			
Parameter	2007		2008		2007		2008		2007		2008		2007		2008	
S_{mea} (m^2)	.17	g	.14	g	1.12	e	.84	f	1.39	d	1.86	b	1.64	c	2.30	a
S_{cal} (m^2)	.15	e	.13	e	1.17	c	.82	d	1.31	c	1.70	b	1.58	b	2.10	a
h (m)	.77	f	.77	f	2.19	c	1.82	e	2.00	d	2.58	b	2.50	b	3.07	a
r (m)	.06	f	.06	f	.19	d	.15	e	.29	b	.26	c	.32	a	.30	b
θ_{out} (rad)	1.28	a	1.28	a	1.31	a	1.28	a	1.06	c	1.14	b	.97	d	1.06	c
XD (10^{-2} m)	4.53	c	4.86	c	1.77	def	3.52	cd	13.06	a	3.36	ce	7.07	b	2.95	cf
YM (10^{-2} m)	56.23	c	52.74	d	51.22	e	53.76	d	55.55	c	53.82	d	62.21	a	59.49	b

Notes: S_{mea}: measured projected side-view area. S_{cal}: calculated projected side-view area. h: plant height. r: radius of stock base. θ_{out}: inclination angle between outmost shoot and ground surface. XD: distance between main axis and mean position of canopy frequency obtained by vertical sections of S_{mea} (Figure 5(A)). YM: mean position of canopy frequency obtained by horizontal sections of S_{mea} (Figure 5(B)). In each item, values with the same letter are not significantly different at 5% level of probability ($n = 10$).

Table 2. Changes of parameters related to the internal force of edible canna cultivated in 2007 and 2008.

	July				August				September				November			
Parameter	2007		2008		2007		2008		2007		2008		2007		2008	
M_{shoot} (N m)	.12	e	.11	e	1.36	d	1.03	de	2.13	c	3.25	b	2.47	c	5.68	a
M_{stock} (N m)	.69	d	.44	d	24.27	c	12.93	cd	53.06	b	68.53	b	61.12	b	132.87	a
$M_{max\text{-}shoot}$ (N m)	6.91	e	4.13	e	21.66	cd	17.02	d	24.86	bc	36.25	a	27.14	b	37.32	a
$M_{max\text{-}stock}$ (N m)	38.68	f	16.51	f	383.46	d	212.76	e	623.94	bc	746.69	*ab*	545.89	c	807.96	a
$\%M_{shoot}$	1.43	f	2.96	ef	4.51	e	4.79	de	5.68	d	7.81	b	6.72	c	11.26	a
$\%M_{stock}$	1.61	e	2.46	e	5.90	d	5.44	d	7.65	c	8.50	c	10.26	b	13.87	a

Notes: M_{shoot}, M_{stock}: internal force by own weight of a shoot and a stock, respectively. $M_{max\text{-}shoot}$, $M_{max\text{-}stock}$: maximum invasion moment of a shoot and stock, respectively. $\%M_{shoot}$, $\%M_{stock}$: $[M_{shoot}] / ([M_{shoot}] + [M_{max\text{-}shoot}]) \times 100$ and $[M_{stock}] / ([M_{stock}] + [M_{max\text{-}stock}]) \times 100$, respectively. In each item, values with the same letter are not significantly different at 5% level of probability ($n = 40 - 248$ for shoot depending on growth stage, and 10 for stock).

($M_{max\text{-}shoot/stock}$, units: N m) was calculated by examining the maximum load tolerable by the shoot (after Matsuo et al., 1986). The load value was read when the relevant shoot completely fell down. The reading was achieved using a string connected to a pulley, with one side connected to the shoot's center of gravity and the other side connected to the hook of a spring balancer. The percentage internal force due to the shoot's own weight (percentage $M_{shoot/stock}$) was calculated by $M_{shoot/stock} / (M_{shoot/stock} + M_{max\text{-}shoot/stock}) \times 100$ (after Hosoi & Imai, 2004). The rhizome fresh weights (FW, units: kg) of the fallen-down plants were also measured.

2.2.3. Mitigation effects

In the present experiment, we compared the mitigation effects of the external and internal forces and the degree of yield loss using regression equations and choosing the largest coefficient of determination. Initially, we calculated the correlations between h and shoot FW in November (Figure 8(A)). Using these, we converted all shoots longer than the target plant length to the target plant length and their expected shoot FW values; thus, we calculated M and $\%M$. Next, using the regression equations between above-ground FW and rhizome FW (Figure 8(B)), we obtained the rhizome FW values expected after shortening of above-ground parts (using the corresponding above-ground FW). Finally, we calculated S_{cal} with changes of .1 m in h and without changing r, θ, or K.

2.3. Statistical data analysis

Regression analysis between the plant parameters was conducted using software (*Excel Statistics 2010 for Windows*, Social Survey Research Information Co. Ltd., Tokyo, Japan). For each plant parameter in different growth stage of edible canna in 2007 and 2008, one-way ANOVA was conducted and afterward, Fisher's LSD tests were applied to determine the significant difference among each value as shown in Tables 1 and 2.

3. Results and discussion

3.1. External force

We plotted the relationships between r and h, rhizome FW and mean θ, r and θ_{out}, and h and θ_{out} as bases to compose Tables 1 and 2. Both in 2007 and 2008, the first two of these four relationships showed relatively high correlations (Figures 6(A) and (B)), whereas the last two did not (Figures 6(C) and (D)). Compared with absolute values of regression coefficients in 2007, the coefficient between r and h was larger, whereas the others were smaller, than in 2008.

The changes in the parameters related to the external force on the edible canna in 2007 and 2008 are shown in Table 1. S_{mea} increased markedly from July to August in 2007 and from August to September in 2008, which was in accordance with a concurrent increase in h. It then

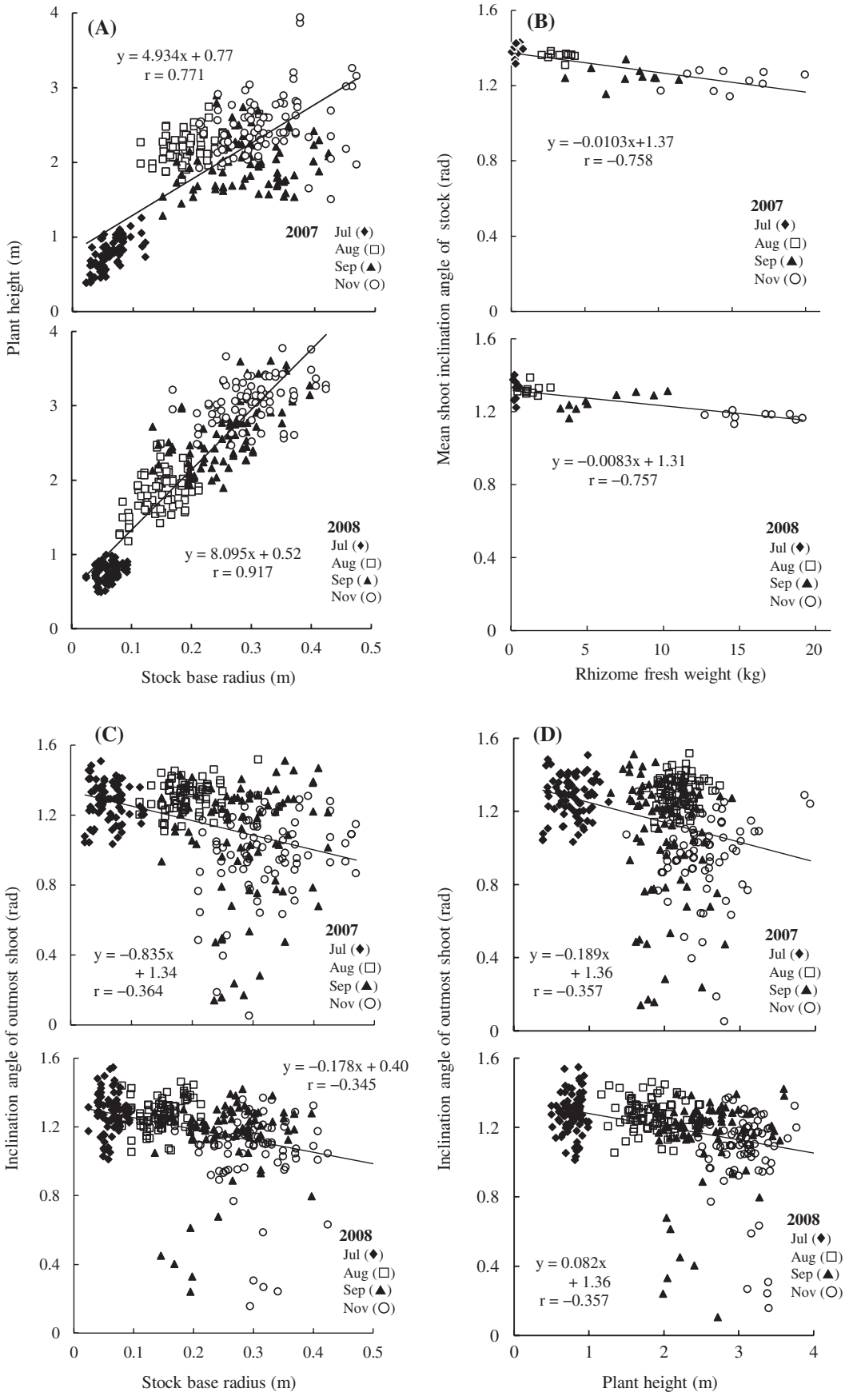

Figure 6. Relationships between (A) stock base radius and plant height, (B) rhizome fresh weight and mean shoot inclination angle of stock, (C) stock base radius and inclination angle of outmost shoot, and (D) plant height and inclination angle of outmost shoot of edible canna cultivated in 2007 and 2008.

increased gradually from September to November in both years due to the stagnation of *h*, increased *r*, and decreased θ_{out}, in parallel with rhizome thickening. *S*, *h*, and *r* values in August 2007 were greater than those in 2008, because greater solar radiation and higher temperatures during May and June (Figure 2) promoted the initial growth of the edible canna. After September, these values reversed due to the typhoon strike in 2007. The trends in *S*, *h*, and *r* were similar to the ontogenetic change in above-ground growth of edible canna previously observed with and without typhoon attack (Imai et al., 1993, 1994).

Both in 2007 and 2008, the *K* (regression coefficient shown in Figure 4) value of S_{cal} decreased during September to November. $K < 1.0$ indicates that the standing crop has scarce mutual shading by leaves and stems. In contrast, $K > 1.0$ indicates that many of the plant parts are located outside the projected side-view area. Therefore, in the present study, the mutual shading by leaves and stems of a stock was larger during July and August than during September and November, when *K* declined due to an increased number of ruptured and dead leaves and an increased inclination of shoots. Furthermore, *K* in November 2007 was smaller (.609) to that in November 2008 (.647) because the plant architecture was disturbed for a substantial period by the typhoon strike in September 2007.

The plant form disturbance by the typhoon greatly affected *XD*; in September 2007, it increased to its maximum value of .1306 m. Among all of the edible canna growth stages, this value was the largest, and most of the plants were affected by lodging. *XD* of the edible canna decreased to .0707 m in November 2007, probably because the fallen-down shoots somewhat recovered their architectures and reduced the horizontal canopy form distributions. Also, after September 2008, several shoots fell to the ground; however, *XM* was not affected, and hence, *XD* was also not affected markedly (data not shown). Once a plant lodges, its canopy architecture is greatly disturbed and *XD* sustains high values; thus, the plant lodges with increased ease. In the case of soybean plants, Ninomiya & Shigemori (1991) reported that *XD* ranged from .0115 m to .2756 m, with a mean value of .0982 m.

YM attained its maximum in November, both in 2007 and 2008 (Table 1), which suggests that the projected area occupied by flower clusters was very small; thus, the frequency of plots including flower clusters was small (data not shown). *YM* after September 2007 was larger than that in 2008 because the upper part of the canopy was broken and/or lost due to the typhoon and the *S* value of the upper part of the canopy was decreased. Ninomiya & Shigemori (1991) emphasized that soybean plants are tolerant to lodging, i.e. that with larger *YM*, plants are more tolerant to lodging due to the location of the projected area becoming converged in the lower canopy (since *YM* is the distance from the top of the canopy). In their experimental plants (soybean), *YM* ranged from .3068 to .46 m, and the average was .3898 m. In our plants (edible canna), *YM* (.5122 m to .6221 m) was higher than was reported for soybean plants; therefore, our values did not so strongly affect lodging.

3.2. Internal force

Equation (8) indicates that the internal force (*M*) is influenced by above-ground shoot *FW*, *L,* and *θ*. There were high correlations between the shoot length and *L* in July to November (Figure 7). *L* was approximately one-third of shoot length in July and August and after September, it had slightly higher regression coefficient, indicating that *L* expanded to upper portion because the larger size of upper leaves and the loss of dead lower leaves tended to increase the height of the plant mass concentration. Also, M_{shoot} and $M_{max\text{-}shoot}$ increased with growth because of increases in shoot *FW* and *L* (data not shown), and θ_{out} decreased in the latter growth stages (Table 1). These suggest plants are getting easy to lodge with progressing growth stage.

Table 2 show changes in the parameters related to the internal force of the above-ground parts of edible canna in 2007 and 2008. M_{stock} and $M_{max\text{-}stock}$ increased with increasing shoot number and increasing shoot *FW* and *L*. The percentages of M_{shoot} and M_{stock} increased with growth because the increasing rates of M_{shoot} and M_{stock}, respectively, exceeded those of $M_{max\text{-}shoot}$ and $M_{max\text{-}stock}$. In 2007, $M_{max\text{-}stock}$ in August was greater than that in 2008 because the greater solar radiation and higher daily average temperatures during May and June (Figure 2) increased the shoot numbers. In 2007, M_{shoot}, $M_{max\text{-}shoot}$, and $\%M_{shoot}$ in September, and all of the parameters in November, were lower than those in 2008. M_{stock} and $M_{max\text{-}shoot}$ were strongly influenced by stem *FW*, *L*, and *θ*. Therefore, the lower values of these parameters in September 2007 might be due to the typhoon-induced lodging of many longer and heavier shoots that we could not measure. In particular, the reason for lower values of M_{stock} and $M_{max\text{-}stock}$ in 2007 than in 2008 was ascribed to smaller M_{stock} values than to shoot numbers per plant because the shoot numbers measured were similar (the numbers of shoots in November were 249 in 2007 and 231 in 2008). Furthermore, $\%M_{shoot}$ and $\%M_{stock}$ in November were smaller in 2007 than in 2008 due to M_{shoot} and M_{stock} in 2007 being about half of the corresponding values in 2008 (Table 2).

3.3. Countermeasures for lodging

In edible canna, S_{mea} (*i.e.* comparable to *S* by multiplying by 2) in November sometimes exceeds 2 m^2, which is far

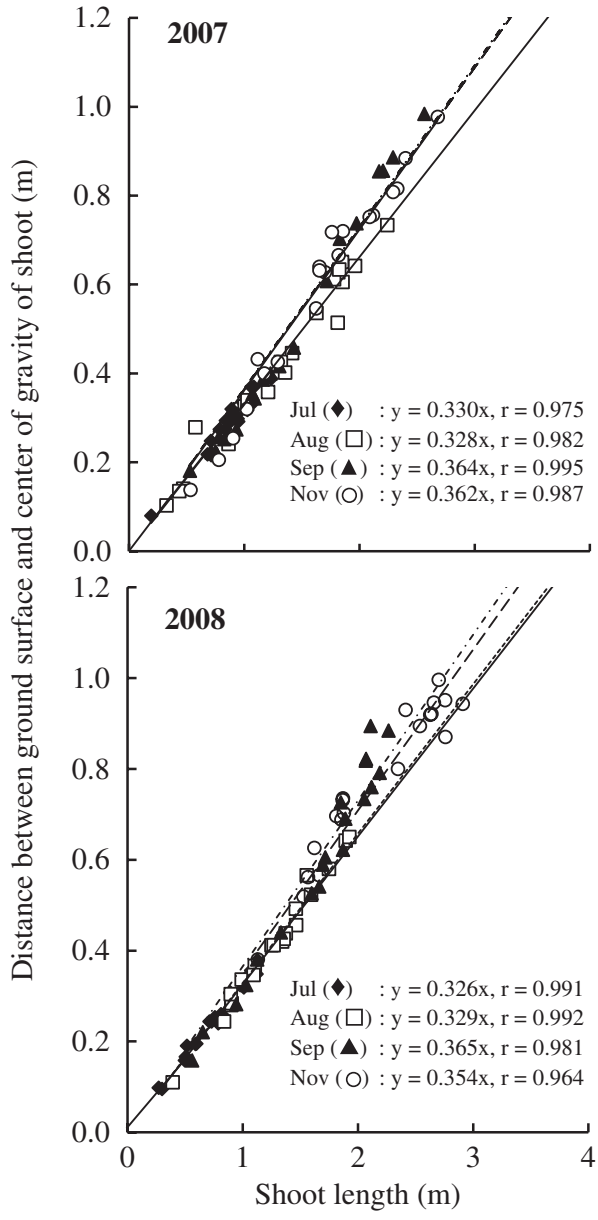

Figure 7. Relationship of shoot length and distance between ground surface and center of gravity of shoot of edible canna cultivated in 2007 and 2008.

greater than for other reported crop species [*e.g.* 65 cm^2 in barley (*Hordeum vulgare* L. cv. Haganemugi; Udagawa & Oda, 1967), 42 cm^2 in wheat (*Triticum aestivum* L. cv. Norin 61; Udagawa & Oda, 1967), and 1,424 cm^2 in soybean (*Glycine max* (L.) Merr.; Ninomiya & Shigemori, 1991)]. The parameters largely influencing *S* are *h*, *r*, and θ. These increased rapidly during July and August. However, this period saw typhoon strike as we met in 2007. The expansion of *r* correlates with rhizome thickening and is necessary for horizontal expansion because of an increased number of rhizomes in the latter growth stage. A larger θ is desirable for *M*; however, in the latter growth stage, edible canna forms many rhizomes, and these become thick by pushing aside the stems. However, the decline of θ is necessary for the formation and swelling of rhizomes. *h* is correlated with the leaf area, and if *h* is too low, a yield decline is induced due to decreased whole-plant photosynthesis. On the other hand, if *h is* too high, lodging is triggered by way of large *L* and shoot *FW*. Therefore, it is necessary, to a certain degree, to shorten *h* from the current value after the middle growth stage. Shortening *h* induces the lowering of *S*, *L*, and above-ground *FW*; thereby reducing *M*.

The above-ground parts of edible canna are prone to over-luxuriant growth because solar energy absorption in the canopy of this plant attains equilibrium during the middle growth stage (120 days after planting; Yajima et al., 1988) and partial shoot cutting increases the root/top ratio by improving the light-interception characteristics (Toyohara & Nishiyama, 1985). The number of shoots is an important component in the smooth formation of yield via stock base enlargement and new rhizome thickening. Hosoi & Imai (2004) calculated S_{cal} and *M*; by considering the solar energy absorption in the canopy and the leaf area index, they concluded that the optimal *h* of edible canna was about 2 m.

Table 3 shows results of the calculation of parameters in relation to lodging mitigation effect by changing potential plant height from 2.0 to 3.0 m. In 2007, there was no mitigation effect on M_{stock} or $\%M_{stock}$ at $h = 2.6$ m. Negative values were obtained above 2.7 m, probably because of the lodging induced by the typhoon. The results of the calculation in 2008 seemed to be more reliable than those in 2007. All of the parameters in 2008 decreased linearly with increasing *h*. The optimal plant height in this case (*h* and shoot *FW* were changed; *r* and θ_{out} were unchanged) was 2.4 m, and the mitigations of S_{cal}, M_{stock}, $\%M_{stock}$, and rhizome *FW* reduction were 35.55, 36.81, 31.76, and 11.28%, respectively.

To improve accuracy of the results, we varied *r* and θ_{out}. Accordingly, we examined the correlations of not only the November data, but also those of four growth periods (July–November). However, there were low negative correlations between *r* and θ_{out} (Figure 6(C)), and between *h* and θ_{out} (Figure 6(D)). Also, there were very poor correlations between *h* and *r* in the November data (Figure 8(C)), although high correlations were obtained between these parameters when data from four growth periods (July–November) were included in the equation (2008 > 2007; Figure 8(D)). Thereafter, we calculated *r* at various values of *h*. We converted individual plants with *r* values larger than the calculated *r* value to the calculated *r* value and obtained S_{cal} without changing θ_{out} or *K* (Table 4). In response to the lowering of *h*, the absolute value and mitigation effect of S_{cal} were larger than those presented in Table 3.

Table 3. Parameters related to expected lodging-mitigation effect by 'shortening of plant height' of edible canna calculated from plants cultivated in 2007 and 2008.

Potential plant height (m)		2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0
S_{cal} (m^2)[a]	2007	1.05	1.13	1.22	1.29	1.35	1.41	1.45	1.49	1.52	1.53	1.55
	2008	1.00	1.08	1.17	1.26	1.36	1.45	1.55	1.64	1.74	1.82	1.90
Mitigation of S_{cal} reduction (%)[b]	2007	33.44	28.27	22.43	18.59	14.38	10.94	7.96	5.73	3.99	2.87	1.99
	2008	52.59	48.56	44.38	40.04	35.55	30.93	26.28	21.89	17.49	13.28	9.47
M_{stock} (N m)[c]	2007	38.57	42.73	47.29	50.29	55.53	58.43	60.27	61.54	61.90	61.03	61.16
	2008	54.74	61.60	68.61	75.60	83.96	91.58	99.36	107.60	113.62	122.55	123.82
Mitigation of M_{stock} reduction (%)[b]	2007	36.89	30.08	22.62	16.68	9.14	4.39	1.39	−.70	−1.29	.14	−.07
	2008	58.81	53.64	48.36	43.10	36.81	31.08	25.22	19.02	14.49	7.77	6.81
$\%M_{stock}$[d]	2007	6.86	7.55	8.27	8.82	9.48	9.91	10.16	10.33	10.35	10.25	10.27
	2008	6.40	7.14	7.89	8.61	9.46	10.23	10.99	11.76	12.32	13.06	13.17
Mitigation of M_{stock} rate reduction (%)[b]	2007	33.18	26.46	19.39	14.03	7.57	3.42	.97	−.71	−.89	.12	−.06
	2008	53.82	48.48	43.13	37.87	31.76	26.23	20.74	15.18	11.14	5.80	5.01
Rhizome *FW* (kg)[e]	2007	13.86	14.07	14.29	14.45	14.63	14.74	14.83	14.89	14.89	14.83	14.83
	2008	13.17	13.43	13.70	13.98	14.28	14.56	14.85	15.14	15.35	15.53	15.71
Mitigation of rhizome *FW* reduction (%)[b]	2007	6.74	5.32	3.87	2.79	1.57	.79	.23	−.18	−.20	.21	.22
	2008	18.20	16.53	14.88	13.12	11.28	9.52	7.74	5.96	4.63	3.50	2.38

[a]S_{cal}: Calculated side-view area. Means only changing plant height without changing radius of stock base, inclination angle of outmost shoot, and correction factors. [b]Means calculated by {(values of actual parameters − values of parameters after shortening) / values of actual parameters} × 100. [c]Own-weight moment for a stock. Shoots longer than objective shoot length were converted to objective shoot weight by the equation in Figure 8(A) and calculated. [d]Means calculated by M_{stock} without changing maximum inversion moment. [e]Shoots longer than objective plant height were converted to shoot *FW* of objective shoot length by the equation in Figure 8(A) and calculated rhizome *FW* by the equation in Figure 8(B).

We have obtained strong correlations between *r* and rhizome *FW* in both years (2007: R^2 = .967, 2008: R^2 = .929) (Figure 8(E)). Furthermore, we examined these for November only (Figure 8(F)) because rhizome *FW* increased rapidly during the latter growth stage (after October). However, the correlations were comparable to those in Figure 8(E) only for 2008 (R^2 = .844), probably because of a lower amount of data. Therefore, in Table 4, we show two patterns of the simulation results, those for the absolute value and for the mitigation rate of rhizome *FW* after shoot shortening. In these results, we do not show the components of internal force because their calculation methods were the same as those in Table 3. The mitigation rates of S_{cal} were adopted based on the 2008 data because these were more reliable than those in 2007. At h = 2.5 m, the mitigation rate of S_{cal} was 35.83% and was equivalent to that at h = 2.4 m in Table 3. Therefore, we considered that the mitigation effect of S_{cal} at h = 2.5 m could be obtained when the desired outcome was only lodging mitigation. However, when we considered the rhizome yield (Figure 8(E)), the % mitigation of rhizome *FW* reduction was high: 37.35% and 73.79% in 2007 and 2008, respectively, at h = 2.5 m. At h = 2.0 m, these values were 66.53% and 88%, respectively, and indicated low rhizome yield. By referring to Table 1, h in November reached 2.5 m in 2007 and 3.07 m in 2008; thus, the decreasing rate of rhizome *FW* would move closer to 0%. However, the results of the simulation were different (2007: 37.35% at h = 2.5 m, 2008: 41.33% at h = 3 m). In Figure 8(E), the data between July and September (the stage of vigorous above-ground growth) were more dominant than those in November (the stage of vigorous rhizome growth with poor above-ground growth); therefore, the rhizome *FW* was underestimated. Therefore, Figure 8(E) was not suitable for estimating rhizome *FW*, even though the correlation was high.

Finally, we examined the results of regression analysis (Figure 8(F)). Although the correlation coefficient of Figure 8(F) was determined to be lower than that of Figure 8(E), the rhizome *FW* reduction rates at h = 2.5 m in 2007 and h = 3.0 m in 2008 were, 5.27 and 5.97%, respectively. These are closer to 0% than those obtained by the regression equation in Figure 8(E); therefore, we decided that use of the regression equation in Figure 8(F) was reasonable. To obtain Figure 8(F), we referred to the regression equation in 2008 because it was more reliable than that in 2007. At h = 2.0 m in 2008, the decreasing rate of rhizome *FW* was large (40.27%), but smaller than that obtained using the regression equation in Figure 8(E). At h = 2.5 m, which was the optimal value of h in Table 4, the decreasing rate of rhizome *FW* was 23.33%, more than 10% larger than that in Table 3. To accord with the decreasing rate of rhizome *FW* at the same level in Table 3, h should be 2.9 m; however, this value would not protect plants from lodging. Similarly, at $h \geqq 2.7$ m, the mitigation effect of the internal force was lower than 20%, and strong wind would induce lodging. Therefore, we concluded that the mitigation effects caused by external and internal forces constrained to about 30% ($h \approx 2.5$ m) and the sacrifice of about 20% rhizome *FW* was reasonable (Table 4). In this trial, we obtained more specific and accurate S_{cal} values than those from our previous work (Hosoi & Imai, 2004) because we changed not only h, but also r.

To improve validity of the results, it is necessary to conduct this type of experiments under diverse growth

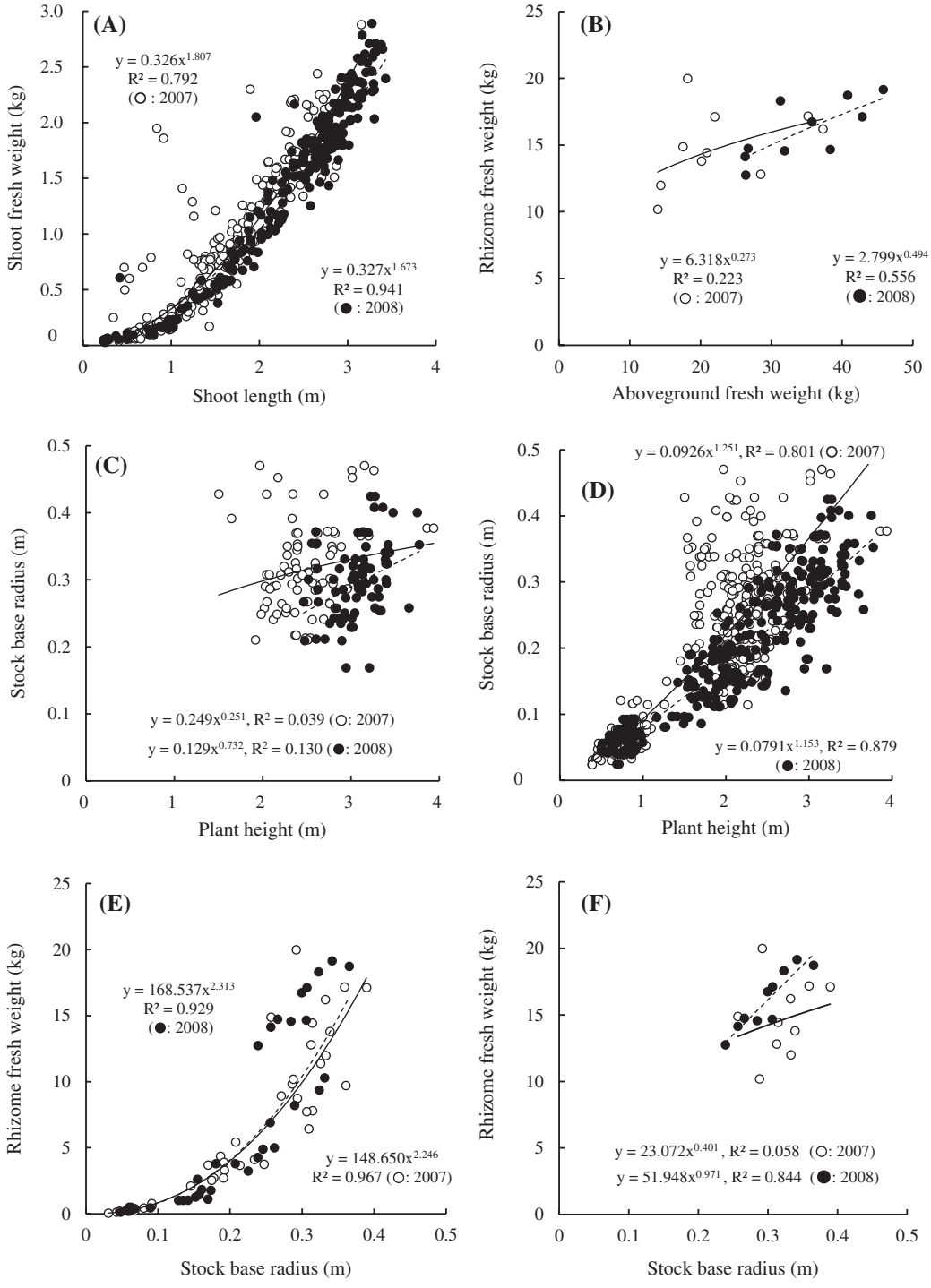

Figure 8. Relationships between (A) shoot length and shoot fresh weight, (B) above-ground fresh weight and rhizome fresh weight, (C, D) plant height and stock base radius, and (E, F) stock base radius and rhizome fresh weight of edible canna cultivated in 2007 and 2008. Data of 8A, 8B, 8C, and 8F were obtained in November and those of 8D and 8E, in July–November.

conditions in the future. In addition, increasing numbers of parameter such that related to θ may be worthy. We also plan to examine edible canna with a reduced shoot length caused by the application of growth retardant (Sumioka & Imai, 2010). One remaining, and important, subject is to clarify the hydrodynamical drag coefficient (C_d), which indicates the pliability of above-ground parts to wind. Examples of C_d measurement are few: an equation for Japanese cedar that includes natural frequency and external force (Shi-igai, 1993) and the use of the six-component force transducer for a conifer (Ishikawa, 2005). The measurement of C_d may be equally important to that of S because C_d fluctuates greatly in response to wind (Shi-igai, 1993). Furthermore, the effect of planting

Table 4. Parameters related to expected lodging-mitigation effect by 'shortening of plant height and radius of stock base' of edible canna calculated from plants cultivated in 2007 and 2008.

Potential plant height (m)		2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0
S_{cal} (m^2)[a]	2007	.95	1.04	1.14	1.21	1.29	1.35	1.41	1.45	1.49	1.51	1.53
	2008	.86	.95	1.04	1.14	1.24	1.35	1.46	1.56	1.66	1.76	1.85
% Mitigation of S_{cal} reduction[b]	2007	40.07	34.35	27.97	23.36	18.48	14.32	10.72	7.97	5.76	4.21	2.99
	2008	59.14	54.89	50.43	45.75	40.87	35.83	30.72	25.84	20.94	16.26	11.96
Rhizome *FW* (kg)[c]	2007	4.97	5.70	6.50	7.37	8.30	9.31	10.39	11.56	12.80	14.13	15.54
	2008	1.93	2.25	2.63	3.08	3.60	4.22	4.95	5.81	6.82	8.02	9.44
% Mitigation of rhizome *FW* reduction[b,d]	2007	66.53	61.62	56.26	50.44	44.14	37.35	30.05	22.23	13.86	4.94	−4.56
	2008	88.00	86.00	83.65	80.88	77.63	73.79	69.26	63.92	57.61	50.15	41.33
Rhizome *FW* (kg)[e]	2007	12.59	12.90	13.20	13.50	13.79	14.08	14.36	14.63	14.90	15.16	15.42
	2008	9.61	10.15	10.69	11.24	11.79	12.34	12.89	13.45	14.01	14.57	15.13
% Mitigation of rhizome *FW* reduction[b,f]	2007	15.29	13.20	11.15	9.15	7.19	5.27	3.39	1.55	−.26	−2.04	−3.79
	2008	40.27	36.92	33.55	30.16	26.75	23.33	19.89	16.43	12.96	9.47	5.97

[a]S_{cal}: calculated projected side-view area. Means calculated with changing plant height and radius of stock base by the equation in Figure 8(D) and without changing the inclination angle of outmost shoot and correction factor. [b]{(values of actual parameters – values of parameters after shortening) / values of actual parameters} × 100. [c]Calculated by substituting values in each of plant height to the radius of stock base using equation in Figure 8E. [d]Calculated by substituting values in each of plant height to the radius of stock base using equation in Figure 8F. [e]Calculated by the method of (c) using values obtained from (d). [f]Calculated by the method of (c) using values obtained from (e).

density should also be examined because we adopted low density (2 m × 2 m) in the present experiment. There have been reports on cell wall component analysis (Ookawa & Ishihara, 1993; Ookawa et al., 2010) and on QTL analysis including identification and introduction of genes to resist lodging in rice (Kashiwagi & Ishimaru, 2004). Overall, these types of investigation may be useful for achieving lodging resistance in edible canna.

Disclosure statement

No potential conflict of interest was reported by the authors.

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*In Japanese.

**In Japanese with English abstract or summary.

Appendix: Abbreviations and symbols

AXS	distance between main axis and left side of plant (m)
b	plant breadth (m)
*b**	normalized plant breadth
C_d	resistance coefficient for perpendicularly projected area of plant
F	external force (N)
FW	fresh weight (kg)
fx(*i*)	section pixel taken vertically
Fx(*i*)	total of section pixels of *fx*(*i*)
fy(*i*)	section pixel taken horizontally
Fy(*i*)	total of section pixels of *fy*(*i*)
h	plant height (m)
K	regression coefficient for S_{cal}
L	distance between ground surface and center of gravity of shoot (m)
M	inversion moment (N m)
M_{max}	maximum inversion moment (N m)
M_{stock}	internal force by stock's own-weight moment (N m)
M_{shoot}	internal force by shoot's own-weight moment (N m)
r	stock base radius (m)
S	perpendicularly projected side-view area of plant (m^2)
S_1	temporary calculated projected side-view area (m^2)
S_2	area of right-angled triangle below ground surface (m^2)
S_{cal}	calculated projected side-view area of plant (m^2)
S_{mea}	measured projected side-view area of plant (m^2)
W_a	above-ground static load (N)
XD	distance between main axis and *XM* (m)
XM	mean position of canopy frequency sectioned vertically (m)
YM	mean position of canopy frequency sectioned horizontally (m)
θ_{out}	inclination angle between outmost shoot and ground surface (rad)
ρ	air density (kg m^{-3})
v	wind speed (m s^{-1})