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Case Studies on High Yields of Paddy Rice in Jiangsu Province, China

II. Analysis of characters related to lodging

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Abstract : To clarify lodging resistance of high yield examples, characters related to lodging of Shan You 63 (F_1 hybrid rice) with 965 gm^{-2} of a brown rice weight were analyzed. There were various factors for early lodging regarding external morphological characters. The lodging index (a distance between fulcra in 5 cm) at the 4th internode from the top (N_4) at maturity was more than 200. High yield of Shan You 63 was obtained under quite dangerous conditions as regards lodging. The reason for increase in the lodging index at N_4 was low breaking resistance. This phenomenon could be explained by a high rate of translocation of non-structural carbohydrate (NSC) and total nitorogen (N) from the culm and leaf to ear, and an extreme decrease in dry weight per unit length of the portion lower than N_4 at maturity. To consistently obtain a yield exceeding 965 gm^{-2} in Shan You 63, it is necessary to develop cultivation techniques to store more NSC, N and dry matter in the culm and leaf sheath and ear.
Key words : Breaking resistance, China, High yield, Lodging index, Paddy rice, Shan You 63.

中国江蘇省における水稲多収穫の事例解析　第2報　倒伏関連形質の解析：天野高久・朱　慶森*・王　余龍*・井上直人**・田中英彦***(京都府立大学農学部・*中国江蘇農学院・**京都大学農学部・***北海道立上川農業試験場)

要　旨：多収水稲の倒伏抵抗性を明らかにするために，汕優63号（玄米収量965 gm^{-2}）の倒伏関連形質を解析した．汕優63号の外部形態には倒れやすい要素が多かった．第4節間（N_4）の成熟期の倒伏指数（支点間距離5 cm）は200を越えた．汕優63号の多収は倒伏に関してきわめて危険な状況下で得られたものである．倒伏指数の増大はモーメントに対して挫折抵抗が相対的に低いためであった．汕優63号において挫折抵抗が低いのは葉鞘＋稈の非構造性炭水化物（NSC）および窒素（N）の穂への移行率が高いこと，N_4以下の単位長さ当たり乾物重が成熟期に著しく低下する特性と関連していた．安定して多収を得るためには，葉鞘＋稈にさらに多くのNSC, N を蓄えるように栽培技術の改善が必要であると考えられた．
キーワード：挫折抵抗，水稲，汕優63号，多収穫，中国，倒伏指数．

In the rice growing area of the central and southern parts of China many cases of lodging by strong winds, heavy rain and excessive use of fertilizer occur[10]. Therefore, to ensure consistent high yields, lodging resistance is one of the most important factors. The culm of F_1 hybrid rice was thick and tough at the time of heading [16]. This is an important characteristic for avoiding lodging and reaping high yields, but various characteristics regarding the culm are still unknown in a range of nearly 1000 gm^{-2} as brown rice yield. After analyzing the characters related to lodging of an example of high yield, it is possible to obtain measures for consistent high yields.

This report is an analysis of characters concerning lodging of Shan You 63 investigated in the previous paper[1].

Materials and Methods

The degree of lodging and characters related to lodging were surveyed for each plot of Ganyu and Donghai Counties in Lianyungang, Jiangsu Province and Kyoto Prefectural University[1]. The degree of lodging was determined based on the standard of Seko[15] at maturity. Three hills with mean culm number from each plot were collected at maturity. Half the number of the culms were picked from each hill at random, then the length of leaf blades from the top to the 3rd (L_1, L_2, L_3) and culm length, internode length (N_1, N_2, N_3

from the top) were measured.

Regarding N_3 and N_4, breaking resistance and bending moment (length from the basal part of an internode that measured breaking resistance to the top of ear × fresh weight of the plant from the basal part of an internode that measured breaking resistance to the top of ear) were measured with leaf sheath attached, and then lodging index (bending moment/breaking resistance × 100) was calculated[15]. For measurement of breaking resistance, a culm bending hardness tester (Fujiwara Seisakusho) was used and during the test, the distance between fulcra of the tester was set as 5 cm.

After removing the leaf sheath, materials were power dried for 2 days at 80 to 90°C, and the dry weight of every internode was measured. Furthermore, the total sugar + crude starch (non-structural carbohydrate : NSC)[17] of each part of the plants was measured at heading and maturity. NSC was fractionated using the method of Murayama et al.[11], then reducing sugar was determined with an auto-analyzer[13].

Twenty days after heading, the ratio of living-leaf sheath in the 4th leaf sheath from the top (culm number with living-leaf sheath/total-culm number × 100) covered N_4, was observed indicated in round numbers. The others, numerical values reported previously[1], such as brown rice weight necessary for analysis, ear number per m^2, Leaf Area Index (LAI) at heading, dry weight of every part of the rice plant at heading and maturity, total nitrogen (N) content, the amount of absorbed N until heading were also applied in this paper.

Results

1. Degree of lodging and external morphology

Lodging was not observed in Shan You 63 and Koganebare in Ganyu County or Xu You 3-2 in Donghai County, but lodging was observed for each Nipponbare in Donghai County and Kyoto. Degree of lodging was 3rd (Medium) and 2nd (Slight), respectively.

Culm length, each internode length, length of the basal internode ($N_4+N_5+N_6$)[9], and ratio of N_6-elongated culm (number of culms which N_6 elongated more than 5 cm/total

Table 1. Culm length, internode length, basal-internode length, and ratio of N_6-elongated culm.

Location	Variety used	Culm length (cm)	Internode length (cm)			
			N_1	N_2	N_3	N_4
Ganyu county	Shan You 63	83.1±4.8	36.7±3.5	21.5±1.2	10.6±1.4	8.4±0.9
	Koganebare	73.9±4.5	34.3±3.2	20.6±1.1	11.0±1.2	6.9±0.6
Donghai County	Xu You 3-2	76.9±4.7	33.1±3.6	21.8±1.4	11.8±1.3	7.6±0.7
	Nipponbare	80.8±4.6	35.2±3.1	22.7±1.0	13.3±1.4	7.2±0.7
Kyoto	Nipponbare	80.3±4.3	38.0±3.0	23.6±1.2	11.1±1.2	6.3±0.8

Location	Variety used	Basal-internode length (cm) *	Ratio of N_6-elongated culm** (%)
Ganyu county	Shan You 63	14.3±3.0	70
	Koganebare	8.0±2.8	0
Donghai County	Xu You 3-2	10.2±2.6	44
	Nipponbare	9.6±2.3	20
Kyoto	Nipponbare	7.6±2.1	3

N_1, N_2, N_3···indicate 1st, 2nd and 3rd···internodes from the top, respectively.
* Basal-internode length : $N_4+N_5+N_6$. ** Ratio of N_6-elongated culm : Culm number which N_6 elongated more than 5 mm/total culm number × 100.

Table 2. Total length of upper-three leaf blades, LAI at heading and product of basal-internode length and ear number per m^2.

Location	Variety used	Total length of upper three leaf blades (cm)	LAI at heading	Basal-internode length* × ear number per m^2
Ganyu County	Shan You 63	139.5±12.4	10.62	5162
	Koganebare	107.0±10.1	7.18	4000
Donghai Ciunty	Xu You 3-2	130.8±11.8	8.17	4529
	Nipponbare	127.9±10.5	7.70	4723
	Nipponbare	124.3±10.9	6.05	3169

* Values showed in Table 1.

Table 3. Breaking resistance, bending moment and lodging index at maturity.

Location	Variety used	Breaking resistance*		Bending moment**		Lodging index***	
		N_3	N_4	N_3	N_4	N_3	N_4
Ganyu County	Shan You 63	551.3	556.1	1070.1	1289.3	194.1	231.9
	Koganebare	413.6	559.0	551.9	659.0	133.4	117.9
Donghai County	Xu You 3-2	453.5	530.6	823.7	1036.7	181.6	195.4
	Nipponbare	330.0	320.7	599.7	725.3	181.7	226.1
Kyoto	Nipponbare	288.0	616.0	849.3	1061.5	295.0	172.0

* Distence between fulcra : 5 cm. ** Bending moment : Length from the base of an internode that measured breaking resistance to the top of ear × fresh weight of the same part.
*** Lodging index : Bending moment/breaking resistance × 100. N_3 and N_4 : Refer to Table 1.

number of culms × 100) were shown in Table 1. The length of culms of Shan You 63 was 83.1 cm and the longest, Xu You 3-2 was shorter than Nipponbare. N_1 of Shan You 63 was between Nipponbare in Donghai County and Kyoto, N_2 and N_3 were shorter than Nipponbare, and N_4 was longer than Nipponbare. The basal internode of Shan You 63 was clearly longer than Nipponbare. Ratio of N_6-elongated culm was 70% in Shan You 63 and extremely high. It was also higher in Xu You 3-2 than in Japanese varieties.

In table 2, the total length of the upper three leaf blades, LAI at heading and the product of basal internode length and ear number per m^2 are shown. The total length of the upper three leaf blades was 139.5 cm in Shan You 63 and very long, and Xu You 3-2 was also longer than that of Nipponbare. LAI in Shan You 63 was 10.62 and the largest, followed by Xu You 3-2. The product of the length of the basal internode and number of ears per m^2 was highest in Shan You 63.

2. Breaking resistance, bending moment and lodging index

In Table 3, beaking resistance, bending moment and lodging index were shown. Breaking resistance of Shan You 63 at N_3 was highest. Breaking resistance at N_4 was larger than Nipponbare in Donghai County, but smaller than that of Nipponbare in Kyoto with a 2nd degree lodging. Breaking resistance of Xu You 3-2 at N_3 was larger than in Japanese varieties, but at N_4, it was smaller than that of Nipponbare in Kyoto. Bending moment at N_3 and N_4 of Shan You 63 were remarkably large. That of Xu You 3-2 was larger than Japanese varieties in China. Lodging index of Shan You 63 at N_3 followed that of Nipponbare in Kyoto and was highest at N_4. Lodging index of Xu You 3-2 at N_3 and N_4 were approximately the same as Nipponbare in Donghai County.

3. Changes in NSC and N content in the culm+leaf sheath during ripening

Changes in NSC were shown in Table 4 and

Table 4. Change in non-structural carbohydrate (NSC) content in the culm+leaf sheath and ear during ripening.

Location	Variety used	Content in the culm +leaf sheath (gm^{-2})		Amount of translocation into ear (gm^{-2})*	Translocation ratio**
		Heading (A)	Maturity (B)		
Ganyu County	Shan You 63	282.4	76.6	205.8	72.9
	Koganebare	174.8	145.8	29.0	16.6
Donghai County	Xu You 3-2	70.1	58.8	11.3	16.1
	Nipponbare	97.2	83.7	13.5	13.9
Kyoto	Nipponbare	199.9	133.1	66.8	33.4

Location	Variety used	Content in ear (gm^{-2})		Amount of accumulation in ear*** (gm^{-2})
		Heading (C)	Maturity (D)	
Ganyu County	Shan You 63	15.1	897.7	882.6
	Koganebare	7.6	518.9	511.3
Donghai County	Xu You 3-2	11.6	763.0	751.4
	Nipponbare	9.0	493.1	484.1
Kyoto	Nipponbare	10.3	574.0	563.7

* Amount of translocation into ear : A−B. **Translocation ratio : $(A-B)/A\times100$.
*** Amount of accumulation in ear : D−C.

those in N in Table 5. NSC of the culm+leaf sheath at heading was extremely high in Shan You 63, but markedly decreased up to maturity. NSC of Xu You 3-2 at heading and maturity were lower than Japanese varieties. In this study, the difference in content at heading and maturity was regarded as the translocation of NSC into the ear[11,12], and then the ratio of translocation [(NSC in the culm+leaf sheath at heading −NSC in the culm+leaf sheath at maturity)/(NSC in the culm+leaf sheath at heading)] was calculated. Strictly speaking, re-accumulation and the consumption by respiration have to be considered[2]. The ratio of translocation of Shan You 63 was extremely high, and that of Xu You 3-2 lower than in Nipponbare in Kyoto. NSC of the ear at maturity was highest in Shan You 63, followed by that in Xu You 3-2.

N in the culm+leaf sheath at heading in Shan You 63 was highest, but was less than Koganebare at maturity. Regarding N, the ratio of translocation was estimated in the same way as for NSC. That of Shan You 63 was highest. N in the ear of Shan 63 was clearly higher than Japanese varieties.

4. Culm-dry weight per unit length at maturity, and ratio of living-leaf sheath in the 4th-leaf sheath from the top 20 days after heading.

Culm-dry weight per unit length at maturity and ratio of living-leaf sheath 20 days after heading were shown in Table 6. The culm-dry weight per 1 cm of Shan You 63 was clearly low at the portion lower than N_4. N_4 of Nipponbare in Donghai County and N_3 of Nipponbare in Kyoto, with low breaking resistance, also showed low values. Ratio of living-leaf sheath in the 4th-leaf sheath was remarkably low in Shan You 63.

Discussion

Degree of lodging showed a positive correlation to length, such as culm length, length of the basal internode, total length of the upper three leaf blades, and ratio of N_6-elongated culm in various cases[3,6,9,15]. Among them, length of the basal internode is particularly important[9]. All of those values were promi-

Table 5. Change in total nitrogen (N) content in the culm+leaf sheath and ear during ripening.

Location	Variety used	Content in the culm +leaf sheath (gm^{-2}) Heading (A)	Content in the culm +leaf sheath (gm^{-2}) Maturity (B)	Amount of translocation into ear (gm^{-2})*	Translocation ratio**
Ganyu County	Shan You 63	7.3	3.5	3.8	52.1
	Koganebare	6.0	4.4	1.6	26.7
Donghai County	Xu You 3-2	6.0	3.6	2.4	40.0
	Nipponbare	5.0	3.0	2.0	40.0
Kyoto	Nipponbare	5.3	2.9	2.4	45.3

Location	Variety used	Content in ear (gm^{-2}) Heading (C)	Content in ear (gm^{-2}) Maturity (D)	Amount of accumulation in ear*** (gm^{-2})
Ganyu County	Shan You 63	2.2	15.8	13.6
	Koganebare	1.7	11.3	9.6
Donghai County	Xu You 3-2	1.6	15.0	13.4
	Nipponbare	1.9	13.2	11.3
Kyoto	Nipponbare	1.4	11.7	10.3

* Amount of translocation into ear : A−B. ** Translocation ratio : (A−B)/A×100.
*** Amount of accumulation in ear : D−C.

Table 6. Dry weight of culm per unit length at maturity and ratio of living-leaf in the 4th-leaf sheath from the top 20 days after heading.

Location	Variety used	Dry weight of culm per unit length (mg/cm) N_1	N_2	N_3	N_4	Lower than N_5	Ratio of living-leaf sheath in the 4th-leaf sheath from the top*
Ganyu County	Shan You 63	4.2	8.1	13.9	14.1	46.4	less than 10%
	Koganebare	3.1	10.7	16.1	22.2	194.5	more than 80%
Donghai Ciunty	Xu You 3-2	3.7	8.3	12.5	16.3	64.2	do.
	Nipponbare	3.2	9.5	12.0	14.7	67.5	do.
Kyoto	Nipponbare	2.9	8.5	11.7	24.0	170.0	do.

N_1, N_2, N_3… : Refer to Table 1. * : Ratio of culm number with living-leaf sheath to total-culm number was indicated in round number.

nent in Shan You 63 (Table 1).

Because there are many factors in lodging, it is difficult to evaluate lodging resistance by a single character. Matsuzaki[9] pointed out that influence of length on the lodging changed according to growth such as the ear number per m^2 and LAI at heading. Influence of ear number per m^2 and length of a basal internode on lodging were represented with the product of both, and the higher value, the greater the degree of lodging[9]. The product of both in Shan You 63 was higher than Nipponbare in Donghai County and in Kyoto (Table 2). Lodging estimated from ear number per m^2 and a total length of the upper three leaf blades[9] was 3rd degree, and the same as Nipponbare in Donghai County and Kyoto. Judging from a combination with LAI and culm length, and LAI and length of the basal internode[9], lodging of Shan You 63 was estimated to reach 5th degree (Severe). As mentioned above, with respect to length and growth, Shan You 63 had various factors of early lodging compared to Nipponbare in Donghai County and Kyoto.

The strength of culm against external force was indicated as the lodging index[15], and characteristics of varieties against lodging were well-represented. When the lodging index obtained at a distance between fulcra 5 cm was more than 200, rice plants were liable to lodge[15]. Lodging index at N_3 of Nipponbare in Kyoto was extremely large and that of Shan You 63 was nearly 200. At N_4, Shan You 63 exceeded 200 (Table 3). Since culms often break at N_4 and N_5 rather than N_3[7,15], it is necessary to pay attention to the lodging index at N_4 in this atudy, Lodging of Nipponbare in Kyoto can be explained in remarkably high value at N_3. Lodging index is the ratio of the bending moment calculated from its own weight and length to breaking resistance. Long-culm length and large LAI of Shan You 63 caused increase in bending moment, resulting a high lodging index. However, those of Shan You 63 also resulted in high $\overline{CGR}$ (mean Crop Growth Rate) until heading, this high $\overline{CGR}$ giving high yields for Shan You 63[1,16]. Therefore, we are unable to avoid increase in bending moment in Shan You 63. Breaking resistance at N_4 of Shan You 63 was smaller than Nipponbare in Kyoto as shown in Table 3. The breaking resistance of Shan You 63 was not in proportion to increase in bending moment. This is related to high lodging index in Shan You 63.

Breaking resistance of culm, including leaf sheath, was composed of culm diameter, thickness of culm wall, development in mechanical tissues of culm, existence of living leaf sheath etc.[15]. These factors are closely related to the amount of distribution of carbohydrate, minerals and dry matter in the culm+leaf sheath after heading[6,8,9,14,15,18]. Hojo et al.[4,5] investigated the relationship between characteristics of matter production and strength of the culm in barley and found that in strong-strawed varieties, translocation of ^{14}C photosynthetic products into the culm+leaf sheath was high, while translocation into the ear was low, and in weak-strawed varieties, translocation from the culm+leaf sheath and leaf blade into the ear was high. In this study, translocation of NSC, a main photosynthetic product[11,13], from the culm+leaf sheath to the ear during ripening was investigated. Shan You 63 clearly showed characteristics of the weak-strawed variety reported by Hojo et al. The higher rate of translocation of NSC and N from the culm+leaf sheath may promote the death of the leaf sheath. Early death of the 4th-leaf sheath from the top, which covered N_4, decreases breaking resistance at N_4[3,6,7,9]. Furthermore, the distribution of dry matter into a portion lower than N_4 decreased in Shan You 63. Low breaking resistance in Shan You 63 is considered to be due to these characteristics.

In 1991, heavy rain and winds were not observed in Lianyungang or Kyoto. Therefore, brown rice yield of 965 gm^{-2} by Shan You 63 was obtained with luck under quite dangerous conditions as regards lodging. To obtain consistently a yield exceeding 965 gm^{-2} in Shan You 63, cultivation techniques to store much more NCS, N, and dry matter in the culm+ leaf sheath and ear are needed.

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